Development of an Izod test for plastics

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The evolution and increasing demand of 3D printers have caused a rise in the use of plastic in industry. For many companies that use 3D prints, the mechanical properties of plastics have become an important factor. In the industrial sector, where there is expensive equipment, it is vital to be aware of the resistance limits of each material.

The purpose of this study was to design and build an Izod test machine in order to check the impact resistance of certain 3D printed plastics. This study was conducted to understand the whole process of designing this Izod test machine as well as the best use procedures, taking accuracy and especially the security and user safety into account.

This specific test was standardised following the SFS-EN ISO 180 Finnish standard and the design was proven to fulfil all the requirements using analytical methods. As specified in the SFS-EN ISO 180 standard, the characteristics of suitable test machines are defined in ISO 13802, which was used in this study as well. Furthermore, it was essential to execute the project according to the requirements of users and stakeholders.

The Izod test machine was designed and built for the Tampere University of Applied Sciences (TAMK), in Finland. The development of the machine was completed successfully after solving all issues in designing, building and testing. Moreover, the machine is working correctly and can test the plastics types as required by the university and the price is under the budged that was available for the project.

This thesis includes the drawings of the system, and a description of the test that were done to show that the machine can be used for testing 3D printed plastics. Furthermore, the user manual can be found in the appendices.

Key words: izod test, impact resistance, impact strength, izod pendulum, impact test.

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GLOSSARY

TAMK	Tampere University of Applied Sciences
Cr	credit
l_{CP}	Length of centre of percussion – Distance from the rotation axis to the centre of percussion (in meters).
l_{CG}	Length of centre of gravity – Distance from the rotation axis to the centre of gravity (in meters).
h_{CG}	Gravity centre height – This is the height of the gravity centre in the releasing point of the hammer (in m). This is measured taking as 0 the lowest point of the hammer's gravity centre trajectory.
g	Gravity constant – Acceleration of the gravity, $9.81 m/s^2$.
I_0	Inertia – Moment of inertia of the hammer along the rotation axis (in $kg \cdot m^2$).
m	Mass – Mass of the body (in kg).
E_P	Potential energy – Potential energy of the body measured from the gravity centre in the releasing point of the hammer (in joules).
E_K	Kinetic energy – Kinetic energy of the body measured from gravity centre in the lowest point of the hammer trajectory (in joules).
v_{SE}	Striking edge speed – Speed of the striking edge in the lowest point of the trajectory.
ω_{CG}	Angular velocity – Angular velocity of the gravity centre in the lowest point of the hammer trajectory.
θ_0	Releasing angle – Angle from where the pendulum is released over the vertical line.
θ_1	Striking angle – Angle where the striking edge is in full contact with the specimen relative to the vertical line.
θ_R	Angle of rise – Final angle of the hammer after one swing over the vertical line.

M_{CG}	Momentum from the gravity centre – This is the momentum generated by the weight of the hammer applied in the gravity centre.
W	Energy of failure – This is the energy of failure of one given specimen. It is given in joules.
$W_{r,material}$	Impact resistance – This is the impact resistance of the given material. The units are joules per square meter.

1 INTRODUCTION

Since the beginning of 21st century, world has experienced drastic changes in technology. Either the evolution of media and mobile phones or the creation of 3D printers and drones, both are new technologies that are going to change the world. Even though these technologies can be used for many purposes, they are the most important improvements for the industry.

However, a new technology always imply an integration in the industry and it requires some issues to be solved. Nowadays, it is possible to make almost whichever shape with plastic 3D prints. Until now it was quite more difficult to make some plastic parts for industry. Nevertheless the most worrying problem of these machines is the plastic resistance of the final pieces despite the high accuracy shapes.

Improving the resistance is as important as knowing the limitation of each 3D printed plastic. That is the main reason why engineers and industry always need testing the materials[1] in order to guarantee the resistance and durability of each part. Impact strength[2] is widely used in technology fields and it is one of the worst properties of 3D printed plastics.

The main purpose of this project is developing an Izod test[3] machine, what includes:

- Research of existing test technologies and standards[4].
- Design[5] of whole machine fulfilling the standards and stakeholders requirements
- Building the machine design and testing to check the requirements

An Izod test machine could be described as a destructive test which uses a small sample (placed vertically) to verify the impact resistance of a specific material.

The aim of this Izod test is providing the University of Applied Sciences of Tampere (TAMK) with an impact resistance test for 3D printed plastics. Although the Charpy test could be used, this Izod test is more suitable for non-metallic materials, with less impact strength.

In this report can be found the designing and building process as well as the engineering process. This includes history of tests, project management, analytic calculus[6], design

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[1] Chemical substance or mixture of substances that has a specific purpose (unlike matter).
[2] Endurance of a concrete material to not being deformed by a strike.
[3] Way or system used for verifying any property of one specific material or system. It is also to prove that a process is working well.
[4] Group of documents that constitute the rules and requirements that must be obey, by a test, to be able to compare measurements with that test.
[5] Creation of a plan for the construction of an object, which also includes the calculus to certify that system can work well. Considering the aesthetic, functional, economic and socio-political dimensions.
[6] Theoretical procedure to calculate a parameter without measuring it experimentally.

models, final built machine and machine testing. Furthermore, there are comparison between analytics and real measurements, and besides, an explanation of the issues found during the project.

2 STRENGTH OF MATERIALS

The theory used in material testing is called "Strength of materials". According to Ryder "The strength of materials is the study of the behaviour of structural and machine members under the action of external loads, taking into account the internal forces created and the resulting deformation. Analysis is directed towards determining the limiting loads (force applied to a structure) which the member can stand before failure[7] of the material or excessive deformation (plastic deformation[8]) occurs."(Ryder 1969)

The applied external forces can be either axial (in the direction of the axis), rotational (the rotation centre is on the axis) or transversal (perpendicular to the axis). However, the internal ones are classified as compressive (axial direction towards the material), tensile (axial direction but opposite direction) and shear (due to faces of the material sliding relative to one another).

According to Vitor "The Mechanics of Materials aims to find relations between the four main physical entities (external and internal forces, displacements and deformations)."(Dias da Silva 2006)

Those entities are also called loads, stresses[9], deflections and strains[10] respectively. Taking into account the continuity hypothesis, there are only three relations between those four physical entities.

$$load \overset{\boxed{1}}{\leftrightarrow} stress \overset{\boxed{2}}{\leftrightarrow} strain \overset{\boxed{3}}{\leftrightarrow} deflection$$

1. Load-Stress relation – This relation is based on force equilibrium between inner and outer forces (Second Newton's law). This relation describes the stress tensor in terms of the external forces and the theory of stresses. It is completely independent of the material properties it just depend of the forces and the shape.
2. Stress-Strain relation – This one defines the rheological behaviour [11]of the material. Since, as a consequence of the complexity of this relation, this behaviour still

[7] Separation of a material into two or more pieces under the action of stresses.
[8] When a material receives a load, it starts to be deformed. If this load is not enough to get the plastic state, when the load cease, the material recover the initial shape. However, if the plastic state is reached, the material never can return to the initial shape, it rest deformed.
[9] Internal pressures that neighboring particles of a continuous material exert on each other.
[10] Measure of the deformation of the material.
[11] Mechanical functioning in terms of deformation and flow matter.

cannot be quantified by deductive means. However, there is an approach based on experimental observation named Constitutive law.

3. Strain-Deflection relation – The last one defines the strain tensor and relates its components to the functions describing the displacement of the points of the body. This relation is also called infinitesimal strain theory which is another approach to the description of the solid deformation. It is essential to assume the displacements as really smaller than any other relevant dimension of the material.

All mentioned before is what Vitor da Silva said. (Dias da Silva 2006)

A stress is defined as a force divided by the surface where it is applied and the unit in SI[12] is the Pascal (N/m^2).

$$\sigma = \frac{F}{A}$$

In this study field, there are some important mechanical properties. Each of them has a different way to study and, obviously, a distinct test to check the material properties. The basic mechanical properties are:

- Yield strength is the property that determines the lowest stress that produces a permanent deformation in a material (elastic deformation limit).
- Compressive strength is a limit state of compressive stress that leads to failure in a material. A compressive test is used to know this property.
- Tensile strength is a limit state of tensile stress that leads to failure in a material. A tensile test is used to know this property.
- Fatigue strength is a measure of the strength of a material under a cyclic loading. This property is checked with a fatigue test and it is obtained a graph of the tensile needed to get a failure depending on the cycles of loading.
- Impact strength is the capability of the material to withstand a suddenly applied load. For this property is used an Izod or Charpy impact test and both give a measure of the energy needed to produce the failure in the material.

Although material testing is part of strength of materials, it can be considered as a science by itself. A science based on putting the resistance of a determined material through its

[12] The international System of Units is the most widely used system of measurement. It includes seven base units (ampere, A; kelvin, K; second, s; meter, m; kilogram, kg; candela, cd; mole, mol), 22 derived units like Pascal (Pa), and 20 decimal prefixes.

paces. However, this element always refer to checking experimentally the mechanical properties of a specified material, not analytically and it should not be confused.

2.1 History of impact testing

As said in *The History and Importance of Impact Testing*, “The earliest publication that we could find on the effects of impact loading on materials was a theoretical discussion by Tredgold in 1824 on the ability of cast iron to resist impulsive forces. In 1849, the British formed a commission to study the use of iron in the railroad industry, which began by considering practical approaches to impact testing.”(Siewert, Manahan, McCowan, Holt, Marsh, Ruth)

Bit by bit, developers started to realise that impact loads had a different effect on materials than static forces. That means the data got until then with other kind of tests was useless to predict the behaviour against an impact load due to some unexplainable failures when they were not supposed to happen.

In 1857, it was invented a drop-weight machine (a heavy weight is released from a determined height vertically over the sample) which was used for over 30 years, especially for railroad steels. Those tests were done using a simple rectangular bar without notch[13]. It was not until 1892 that LeChatalier the notched specimens[14]. He realised that some steels with ductile behaviour could show a fragile failure if the specimen was notched.

Afterwards, between 1895 and 1922, lots of countries realised about the importance of impact testing and they started developing the standards. Both, international and national standards were defined. Thus the procedures and consensus standards became more robust. Many standard bodies were established, actually, the IATM “International Association for Testing Materials” was established in 1901.

In 1898 Russell made a report where he pointed out that there was not any machine able to determine anything beyond if the specimen failed or withstood the impact strength. He

[13] Angled or v-shaped cut in surface of the specimen.
[14] Sample of a material for study with some shape, size and conservation requirements.

designed and built a pendulum capable to "measure the energy actually absorbed in breaking the test bar."(Siewert, Manahan, McCowan, Holt, Marsh, Ruth). This pendulum machine was based in the same concept as current pendulum impact test machines. Furthermore, he had already included the corrections for friction losses and calculation and comparison of the centres of gravity and percussion. Thanks to that fact, impact test machines became significantly more compact. Besides, provided the bases for future research despite the fact that those reports were quite simplistic.

Even though Russell invented the impact test machine used today, the machine took the name of G. Charpy, a Frenchman who put much effort to standardise the test. In fact, Charpy acknowledges the Russell's improvement stating: "Russell described in a paper presented in 1897 at the American Society of Civil Engineers some 'experiments with a new machine for testing materials by impact.' The machine he is using is designed to determine the work absorbed by the rupture of a bar, for this, the ram used appears in the form of a pendulum arranged in such a way so that when it is released from its equilibrium position, it meets the test bar in passing through the vertical position, breaks it and afterward rises freely under the influence of the acquired speed. The difference between the starting height and the finishing height of the pendulum allows evaluation of the work absorbed by the rupture of the bar."(Siewert, Manahan, McCowan, Holt, Marsh, Ruth)

In 1922, took place a Symposium on Impact Testing of Materials in New Jersey. The Symposium included the results of a survey sent to 64 testing laboratories of US and 23 of them gave positive feedback about developing an ASTM standard for impact testing. So it took 10 years, since 1923 until 1933, to publish the "Tentative Methods of Impact Testing of Metallic Materials" (annual reviewed).

Afterwards, in 1946, ISO (Standard Organisation for Standardisation) was founded. Even though ISO is not a real acronym of Standard Organisation for Standardisation, the founders decided to give it because that term is derived from the Greek 'isos' that means equal. Delegates from 25 countries had a meeting in London at the Institute of Civil Engineers and they decided to create this organisation in order to facilitate the international coordination and unification of industrial standards. So, on 23rd of February, ISO officially became an organisation. Nowadays, they have published over 22138 International Standards and they have different members from 161 countries.

After almost one century, there have been some changes like the strike edge shape or the clamp edge radius. However, since then, both Charpy and the Izod test had not changed significantly and we are still using the swinging pendulum and trying to reduce the friction losses in order to have a better accuracy in the measurements.

2.2 Izod test functioning

For this Izod test machine it has been used the Finnish standards SFS-EN ISO 180 translated from Finnish to English and two amendments for that standard. Furthermore, it has been used the international standard ISO 13802 in order to find the principles, characteristics and verification[15] of suitable test machines as recommended in SFS-EN ISO 180. In order to have more information it has been also used ASTM D256-06, but the test is not done following this last document.

All these standards documents cover the determination of plastics impact resistance, using standardised pendulum-type hammers and breaking standard specimens with one pendulum swing. In this chapter it is going to be shown the most important requirements and how to fulfil them as well as the calculus and theory methods used to design the test.

The functioning of this machine is pretty easy to understand, but first it is important to know how a simple pendulum works. A simple pendulum is a weight suspended from a pivot so that it can rotate around it. The movement of a pendulum is in the vertical plane so the gravity force (weight) is going down. If the pendulum is raised to one specified height (or angle) part of the gravity force is used for compensating the rope tension and the rest is used for the movement.

When the pendulum is in the lowest position, the gravity part for the movement disappear (all the force is used to counteract the tension). However, the pendulum has already speed which produce that the pendulum takes a few more distance to stop. It is not that easy to see that the place where the pendulum stops is at the same height as it started if we do not consider energy losses.

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[15] Proof that the calibration of an instrument is acceptable.

Another way to deal with this physics problem is going through with the mechanical energy conservation. Ideally, a simple pendulum do not have changes in the mechanical energy without external interactions. So it is possible to say that in any point of the way, the pendulum should have the same mechanical energy.

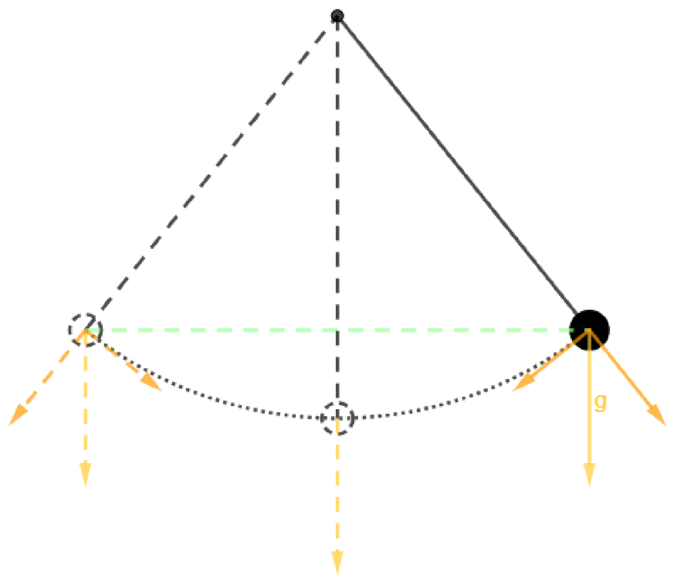


Figure 1 Forces in a simple pendulum

This energy is composed by some other energies, like the kinetic[16], potential[17] and elastic[18] energies. In this concrete case, it can be said that in the first and the third points, the pendulum has only potential energy because it is in some height but it does not have kinetic because of the lack of speed. However in the second one, it only has kinetic energy because there is no height lowest point. So, mathematically:

$$\sum E_m = 0$$

$$E_{m_1} - E_{m3} = E_{p1} - E_{p3} = 0$$

$$m \cdot g \cdot h_1 - m \cdot g \cdot h_2 = 0$$

$$h_1 = h_2$$

This means that the pendulum gets the same height in ideal conditions.

If the specimen is added in this simple pendulum system, the equation should change for taking into account the energy spent in order to brake the sample. Thus, the initial energy

[16] Energy of a body or a system due to the motion of its mass.
[17] Energy of a body or a system owing to the distance of a really heavy body (like Earth, gravity).
[18] Energy of a body or a system because of the deformation of another body (like a ball pressing a spring).

should be the sum of the final energy plus the energy used in the strike and it would be something like:

$$E_{m1} = E_{m3} + E_{strike}$$

Then, with this it would be possible to know the energy used for the failure if we are aware of the mass and the height of release and maximum ending height.

$$E_{strike} = mgh_1 - mgh_3$$

However, this is not that easy. In real life, a pendulum is not oscillating[19] forever. Due to energy losses this model is far away from the reality, so it is really important keeping them in mind and try to reduce them in order to have reliable and good results. The energy lost by the pendulum during the breakage of the specimen is the sum of the following:

- Energy to initiate the fracture of the specimen – There is always some energy wasted just to start the fracture of any material that produce a stresses gathering and makes the failure easier. It is really easy to see in some plastic packages, when it starts to fracture, the crack is made bigger easily.
- Energy to propagate the fracture across the specimen – This is an interaction between the molecules of the material, but is pretty insignificant.
- Energy to throw the free end of broken specimen – This loss is really important because there is some energy used to give some speed to the broken part. Here applies the toss correction[20].
- Energy to bend the specimen – The energy needed to bend apart from braking it.
- Energy to produce vibration in the pendulum arm – There is also a really annoying loss caused by the vibrations due to the strike and, as we will see later, there is a way to reduce them.
- Energy to produce vibration or horizontal movement of the machine frame or base – This is pretty similar to the last one, the inertia of the pendulum produce some reactions in the foundation of the machine. Then the foundation has to be heavy and stiff enough to avoid this.
- Energy to overcome friction in the pendulum bearing and in the indicating mechanism, and to overcome pendulum air drag – This is just the energy losses due to the friction with the air and the mechanical friction in the bearings.

[19] To swing or move to and fro, forward and back or side to side repeatedly.
[20] Toss correction consists of leaving the broken part over the clamp and analysing the energy lost (deleting all the braking energies). This is just an approximation.

- Energy to intend or deform plastically the specimen – This is the same as the energy to bend it but is the plastic deformation of the specimen instead of the elastic.
- Energy to overcome the friction caused by the rubbing of the striker over the face of the bent specimen – This is a really small energy due to the friction between the specimen and the striker.

It is true that these losses of energy and maybe even more are present and affect the swinging making it a non-ideal pendulum. However, in engineering is important to be critical in order to improve the efficiency (faster with high accuracy). For engineers the most important is making hypothesis and demonstrate that they are applicable. So, now it is needed to despite some losses depending on some factors:

- For relatively brittle[21] materials – Fracture propagation energy is small compared with the fracture initiation energy and toss correction may represent a very large fraction of the energy absorbed.
- For tough, ductile[22], fibre filled, or cloth-laminated materials – The fracture propagation energy could be larger than fracture initiation. Propagation energy, arm vibration energy and rubbing friction are quite more significant for those materials. Also, bending and indentation losses may be appreciable with soft materials.
- In a well-designed machine (rigid and heavy) – The losses owing to foundation movement and bearing friction should be very small.

It is important to know that some materials, a critical width of specimen may be found below which specimens will appear ductile and above which they will appear brittle.

2.3 Project management

The planning of this project has been done using the Work Breakdown Structure (WBS) for splitting the project in simpler parts. Also a Gantt chart which provides a complete schedule to develop the project correctly.

[21] Having hardness and stiffness but breaking easily.
[22] Capable of being hammered out thin, as most of the metals.

The WBS is a way to organise hierarchically the different tasks that must be done during the project. In WBS, all the elements of the project are separated in different work packages; we have to define the necessary work packages to develop the project. The Work Breakdown Structure of this project is the following.

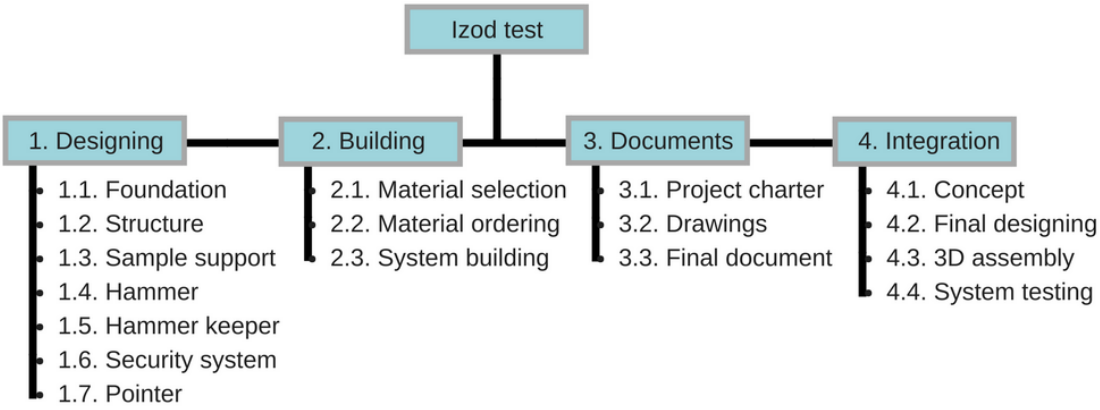


Figure 2 Work Breakdown Structure

To proceed with the Gantt chart, firstly is indispensable to know what activities have to be done to get the parts of the WBS. In the next table all the activities are identified.

Table 1 Identification of the different tasks of the project

CODE	Activity	Description
1.1.	Design the foundation	Make a foundation design taking into account the weight and the size.
1.2.	Design the structure	Design a structure which supports the loads.
1.3.	Design the sample support	Design a suitable support for the sample used in this kind of test.
1.4.	Design the hammer	Design the hammer that fulfil all the requirements in the standards.
1.5.	Design a hammer keeper	Design a system to keep and release the hammer without unnecessary vibrations.
1.6.	Design a security system	Design a security system in order to prevent issues
1.7.	Design a pointer and scale	Design a pointer system that stands in the highest position of the pendulum swing.
2.1.	Select the materials	Select the best materials that can be used for the system.
2.2.	Order the materials missing	Order those designs that absolutely cannot be changed.
2.3.	Build the system	Build the system using all the parts ordered and selected.
3.1.	Write a project charter	Write a project charter in order to clarify the aim of the project.
3.2.	Make the drawings	Draw the blueprints for building the system.
3.3.	Write the final document	Write the final document of the project.
4.1.	Define the concept	Define the designing idea bearing in mind.
4.2.	Make the final design of every parts	Make the 3D designs of all parts of the system for the assembly.
4.3.	Make the 3D assembly	Make a 3D assembly using all the parts that have been drawn.
4.4.	Test the system	Check that the system is working how it should.

These are all the activities done during the engineering phase of the project. The subsequent phases are not included in this project.

Once the activities are described it is also important to recognise the dependency relationships between activities. In the following table there are the order of execution and precedence of each activity.

Table 2 Dependency relationships between activities

CODE	Activity	Preceded[23]
1.1.	Design the foundation	4.1.
1.2.	Design the structure	1.4.
1.3.	Design the sample support	4.1.
1.4.	Design the hammer	4.1.
1.5.	Design a hammer keeper	1.2.
1.6.	Design a security system	1.5.
1.7.	Design a pointer and scale	1.5.
2.1.	Select the materials	1.5.
2.2.	Order the materials missing	1.5.
2.3.	Build the system	2.2.
3.1.	Write a project charter	---
3.2.	Make the drawings	4.2.
3.3.	Write the final document	4.4.
4.1.	Define the concept	---
4.2.	Make the final design of every parts	1.5.
4.3.	Make the 3D assembly	1.5.
4.4.	Test the system	2.3.

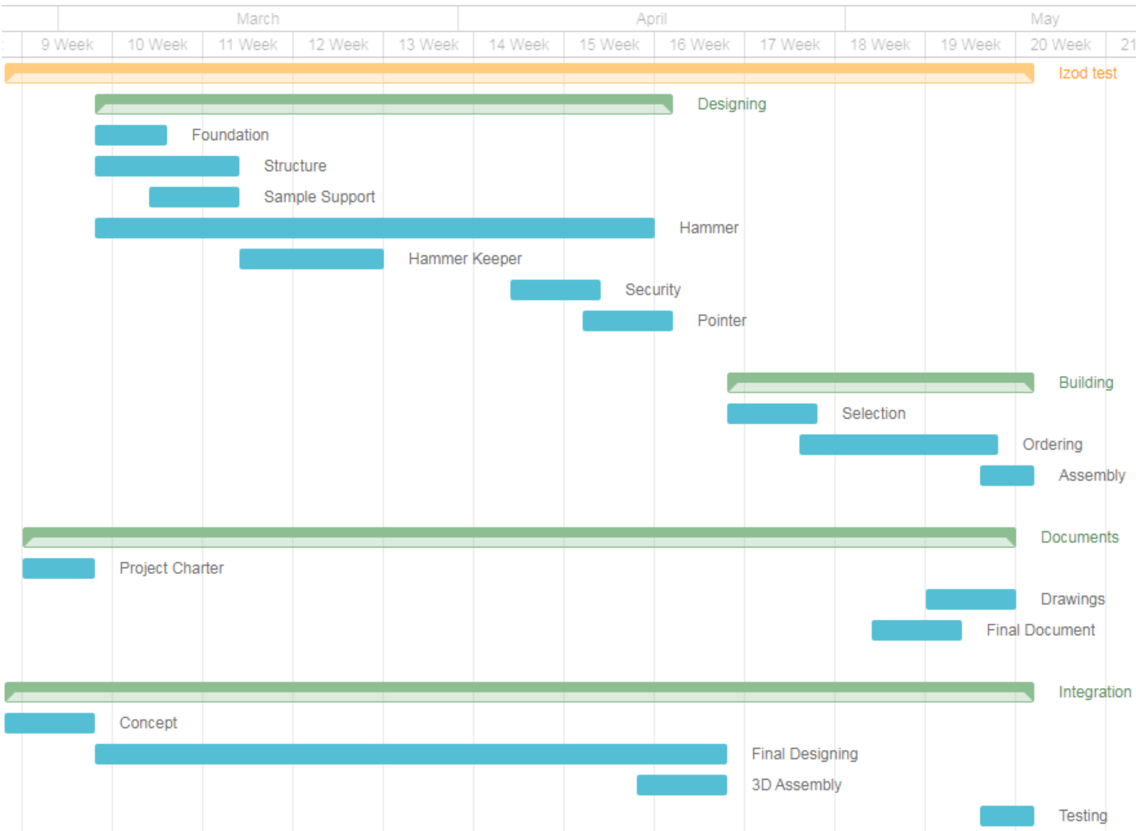
Now every activity has been defined and it is known its precedence. However, the next step is predict approximately the time dedication for each activity or the estimate necessary human resources to develop each activity. This is shown in the table below.

[23] Immediate predecessors (potential ligatures) must be identified. Precedence relationships are only established between tasks, not between deliverables or work packages that group a set of tasks.

Table 3 Estimation of the resources on each activity

CODE	**Activity**	**Hours**	
1	1.1. Design the foundation	5	100
	1.2. Design the structure	10	
	1.3. Design the sample support	10	
	1.4. Design the hammer	45	
	1.5. Design a hammer keeper	15	
	1.6. Design a security system	5	
	1.7. Design a pointer and scale	10	
2	2.1. Select the materials	20	70
	2.2. Order the materials missing	20	
	2.3. Build the system	30	
3	3.1. Write a project charter	25	70
	3.2. Make the drawings	15	
	3.3. Write the final document	30	
4	4.1. Define the concept	10	60
	4.2. Make the final design of every parts	20	
	4.3. Make the 3D assembly	20	
	4.4. Test the system	10	
Total hours		**300**	

Even though some activities does not requires a lot of time, like ordering the materials, it takes several days to have the parts. This is not visible here, that is why it is important to make a schedule, the Gantt chart. The next figure shows the Gantt chart of this project.



Picture 1 Project schedule, Gantt chart

Using this schedule it is possible to know how much time is available to carry out each activity and when each part should be done to make a good job.

2.4 Theoretical basis

Here there are explained the theoretical concepts used in the rest of the project. This is important if some of the technical concepts are not well known in order to understand the calculus made.

2.4.1 Centre of mass

It is really common in physics that there is a mass point studied and some properties have to be calculated. In the real world, there is not a single problem where a mass point needs to be studied. In the reality, everything has a volume and a shape, and obviously, this is not the same as one point with mass.

However, scientists found a way to approach every knowledge about the mass point to volumetric masses. This is the mass centre method. If there are different mass points distributed in the space, it is possible to find another mass point in the space that moves as if all the mass of the system were concentrated at that point.

If a volumetric mass is considered as a lots of mass points it is possible to find an exact point where all the body's mass could be concentrated and it would be acting as the volumetric mass. This is the centre of mass and the way to calculate it is pretty simple when there are some particles. Taking a reference point, and an axis system (x, y, z) for example, the equation would be

$$\vec{x}_{CM} = \frac{\sum_{i=1}^{n} m_i \vec{x}_i}{M}$$

Where $\vec{x}_{CM}$ is the place of the centre of mass expressed as a vector with 3 components, m_i is the mass of each particle and $\vec{x}_i$ is the position of that particle. M is the sum of all the particle masses and n is the number of particles.

However, when it is a volumetric body, the number of mass points is excessive and it is used the integral form.

$$\vec{x}_{CM} = \frac{1}{M} \int \vec{x} dm$$

But this is only possible to solve when the shape of the body is something mathematically possible to express. Otherwise, it would be used the finite elements method that it is not necessary to explain due to its complexity.

The most important of the mass centre is that any force applied in any direction that pass over to the centre of mass will produce a linear movement in that direction without generating momentum and therefore rotation.

2.4.2 Centre of percussion

"The centre of percussion is a point on a pin-supported object where a perpendicular impact will not produce reaction force at the pivot point."(Harvard Natural Sciences)

To understand this concept, it is taken a bat suspended from a horizontal stud by a U-bolt as showed in the picture below. The bat is able to rotate about the point of suspension and this point is able to move horizontally.

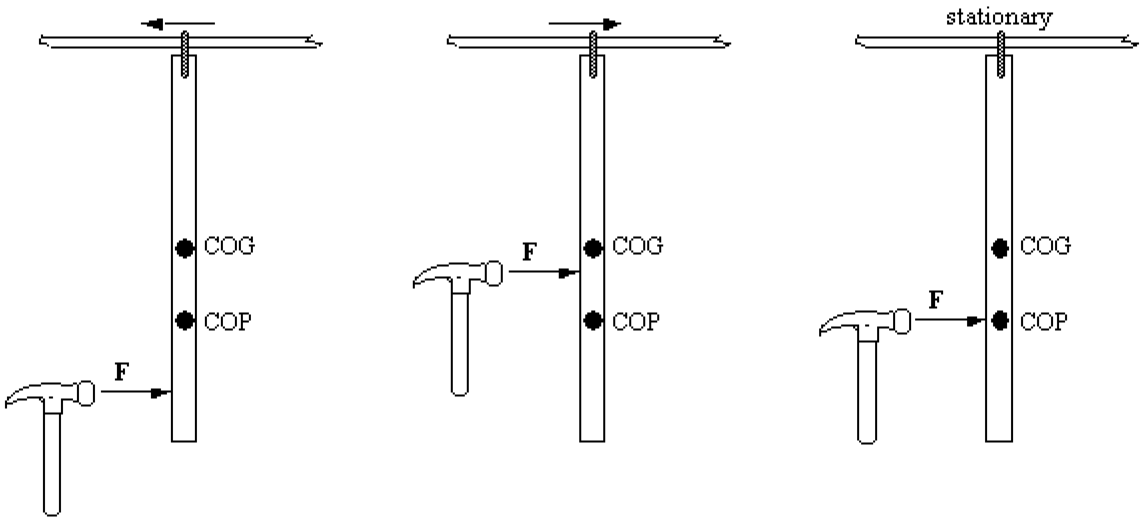


Figure 3 Center of percussion explanation

In this case, if the bat would be struck just on the centre of gravity (centre of mass), the post would just move to the right. If the hit would have been above this point, the beam must move to the right and rotate clockwise. However, this bar is free on the horizontal movement, so if the bar is hit on a point between the centre of gravity and the centre of percussion, it will move to the right and counter clockwise. But if the hit is below the centre of percussion, the movement will be to the left and counter clockwise as well. Finally, if the strike is just on the centre of percussion, the suspension point is not going to move and obviously it will rotate counter clockwise because the hit is under the centre of gravity.

This is widely used in baseball where it is important to get a good strike. When the batter strike the ball, it goes further if it touches the centre of percussion of the bat instead of the mass centre.

In this case, the point of suspension can move horizontally, but in a pendulum, that point is affixed. So this movement (if the impact is not on the centre of percussion) results in some forces and vibrations. It is important to avoid these sort of forces because it is a cause of severe energy losses.

In order to find analytically the centre of percussion of a pendulum, it is required the rigid body dynamics equations. Firstly, it is considered an arbitrary shape for a solid with a point P of rotation and point G of centre of gravity (already known). After, it is presented an analogy of the Newton's second law with torque instead of force.

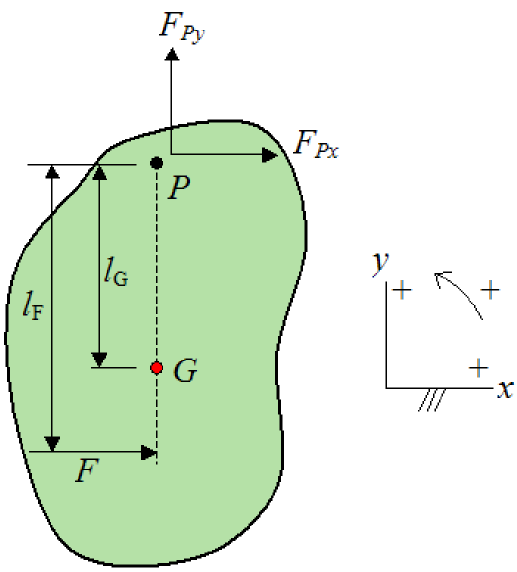


Figure 4 Scheme of the body to find the centre of percussion

$$\sum_{i=1}^{n} \vec{T_i} = I \cdot \vec{\alpha}$$

The force F is already on the centre of percussion (at a distance of l_F from P) because it is already known that the horizontal force in the point P it is going to be 0. This means that there will be no reaction force at P due to the impact force F. Using the torque equation on P there is the following.

$$\sum T_p = I_P \cdot \alpha$$

Where T_P is the sum of the moments about the fastened point P and I_P is the inertia of the body about P. The symbol α is the angular acceleration. This acceleration can be expressed using the acceleration of the centre of mass. And the only torque is the one occasioned by the force. So the equation should be something like this

$$\alpha = \frac{a_{CM}}{l_G}$$

$$\sum T_P = F \cdot l_F$$

$$F \cdot l_F = I_P \cdot \frac{a_{CM}}{l_G}$$

Where a_{CM} is the linear acceleration of the gravity centre. Thus, using the Newton's second law, it is got that

$$F = m \cdot a_{CM}$$

$$l_F = \frac{I_P}{l_G \cdot m}$$

With this result, it is possible to say that the position of the centre of percussion depends on the inertia, the mass and the position of the centre of mass following the equation above.

2.4.3 Moment of inertia

"The moment of inertia is a measure of an object's resistance to changes to its rotation."(The ARC). Usually, the inertia of one solid about one point is given using a tensor. As it is shown above, the inertia tensor determines the torque needed to get a specific angular acceleration of that body.

The inertia is an extensive property[24] that can be defined with the second moment of mass with respect to the distance from the axis of the measurement r.

$$I = \int r^2 dm$$

The square radius integrated for each mass differential of the rigid solid.

The tensor of inertia is a symmetric matrix of 3 by 3 where are expressed all the moments of inertia of a solid about one point in the 3 orthogonal axis. It depends on which axis is rotating, the body has one specific inertia or another.

[24] An extensive property of a system is that type of property that depends on the system size or the amount of material in the system. This means that if the system is divided into some subsystems, the property of the system will be the sum of the extensive property measured for each subsystem.

2.4.4 Fictitious force

A fictitious force is an apparent force that acts on all masses whose motion is described using a non-inertial[25] frame of reference[26]. One example of non-inertial system is a lift that is going down and it starts to stop before reaching the ground floor. When the elevator is stopping, it is easy to feel a force down, as if people were heavier. In fact, in that moment people is heavier because the acceleration is bigger than the gravity. But those evident forces are named fictitious forces.

Therefore when there is a non-inertial system to evaluate, it is indispensable taking into consideration the fictitious forces. In a rotational system there are important fictitious forces a part from the dragging force, those are the centrifugal and Coriolis forces. The dragging force is that one which depends of the tangential acceleration. The centrifugal force is the force due to the normal acceleration of a rotation movement and is going away from the centre of rotation. The Coriolis force is a complementary force caused by the movement of a particle in a non-inertial system, but for this project is not necessary to go deeper in this because it is not applying for this pendulum.

The mathematical equation that describes the total force applied on one non-inertial system is

$$\sum \vec{F} = -m \cdot \overrightarrow{a_M} - m \cdot \overrightarrow{a_0} - m \cdot \vec{\dot{\omega}} \times \vec{r} - m \cdot \vec{\omega} \times (\vec{\omega} \times \vec{r}) - 2 \cdot m \cdot \vec{\omega} \times \overrightarrow{v_M}$$

Where $\overrightarrow{a_M}$ and $\overrightarrow{v_M}$ are the acceleration and the velocity relatives, in this case they are 0. The $\vec{\omega}$ and $\vec{r}$ are the angular speed and the radius of the movement. The $\overrightarrow{a_0}$ and $\vec{\dot{\omega}}$ are the acceleration of the reference system and the angular acceleration respectively.

For this system it is possible to use the following equation, which is just a simplification of the previous formula.

$$\sum \vec{F} = -m \cdot \vec{\dot{\omega}} \times \vec{r} - m \cdot \vec{\omega} \times (\vec{\omega} \times \vec{r})$$

Also, to make it easier to solve, it is better to define the direction of every vector and determine if each term is positive or negative. Considering that the pendulum is making the swing from the right to the left, the vector of the angular speed goes inside. The radius

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[25] Everything that is accelerating, so acceleration different to 0, is a non-inertial system. An inertial system is that which is moving, or not, to constant speed.

[26] The frame of reference is a coordinate system that define the 0 point and the directions of each dimension. The Cartesian coordinates are the most common reference frame used until 3 dimensions with 3 directions and one 0 point where x, y and z worth 0.

is always pointing the radial direction and the angular acceleration is going inside the first part of the swing and going outside the second part, in the lowest point of the trajectory is 0. So, there will be two equations, one for the first part and another for the second one and, respectively they are

$$F_1 = m \cdot \dot{\omega} \cdot r \left(\hat{\theta}\right) + m \cdot \omega^2 \cdot r \; (\hat{r})$$

$$F_2 = -m \cdot \dot{\omega} \cdot r \left(\hat{\theta}\right) + m \cdot \omega^2 \cdot r \; (\hat{r})$$

With this is possible to calculate the force produced by the hammer swinging.

2.4.5 Torque

The torque is a kind of moment. A moment is the product of a distance by a physical quantity. In the case of the torque is the product of the distance by a force. However, the torque depends on other factors because the force is a vector, which means that has a magnitude and a direction. Sometimes is also defined as the rotational force.

Then, the torque could be defined as the product of the force by the perpendicular distance to the centre of rotation. However, the correct way to define should be the cross product between the position vector of the force and the vector force. Mathematically,

$$\vec{\tau} = \vec{r} \times \vec{F}$$

The module of the torque can also be calculated as,

$$\|\vec{\tau}\| = \|\vec{r}\| \cdot \left\|\vec{F}\right\| \cdot \sin(\alpha)$$

Where α is the angle between the two vectors.

Now, taking a beam which is held by a rotation point, it is possible to calculate the potential energy without knowing where is the gravity centre. In the figure below it is possible to see a beam with the centre of rotation in “O”. There is a force F_A applied in an arbitrary point “A” and the weight of the beam is applied in the gravity centre “G”. The beam is not moving, so this is a static case.

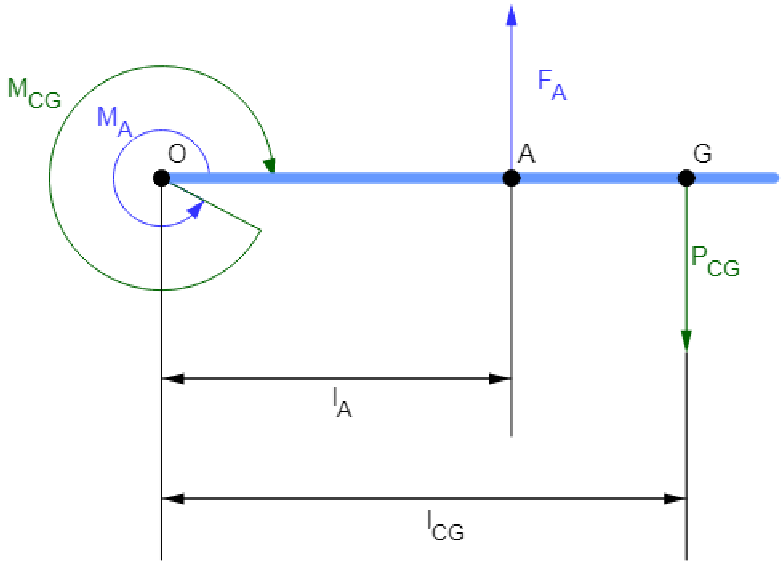


Figure 5 Torque counterweight principle

In statics, the sum of forces and torques are equal a 0 because the acceleration and the angular acceleration are 0. In this case the following equation applies,

$$\sum_{i=0}^{n} \vec{F_i} = 0$$

Both forces are in the vertical direction, so there is no force in horizontal.

$$F_A - P_{CG} = 0$$

Also, the torque sum has to be 0.

$$\sum_{i=0}^{n} \vec{\tau_i} = 0$$

$$\overrightarrow{M_A} + \overrightarrow{M_{CG}} = 0$$

Considering that the distance of the mass centre l_{CG} is not known, but the force F_A is measured, and obviously the distance of the point "A" is known. The torque of the mass centre in the centre of rotation is

$$\overrightarrow{M_{CG}} = -\vec{l_A} \times \vec{F_A}$$

The angle between the distance of the arbitrary point and the force needed to have a static system are orthogonal, the cross product is

$$\overrightarrow{M_{CG}} = l_A \cdot F_A \left(\hat{k}\right)$$

The potential energy of one solid is defined as the mass by the height of the gravity centre by the gravity constant as,

$$E_P = mgh$$

In this case, the product of the mass by the gravity constant is the weight of the beam. The height, if it is raised to a given angle and the lower angle is different to 0,

$$E_P = P_{CG} \cdot l_{CG} \cdot (2 + \cos(180 - \theta_0) - \cos(\theta_1))$$

Looking at that equation, it is possible to deduce that the product of the weight by the distance to the centre of gravity is the torque of the centre of gravity. As said before, that torque is equal to the torque in the arbitrary point.

$$E_P = l_A \cdot F_A \cdot (2 + \cos(180 - \theta_0) - \cos(\theta_1))$$

That is the potential energy of the hammer which is released from a given angle θ_0.

3 DEVELOPMENT

This chapter is entirely dedicate to explain the designing and building process and the testing made following the standards. The designing also includes the calculus necessary to ensure that system is going to be reliable.

3.1 Requirements

In requirements it is possible to make a distinction between two types of them. The first ones are the requirements stated by the standards. There are also costumer requirements due to the use of this machine.

3.1.1 Stakeholder requirements

The first requirement it is pretty simple, the machine has to be secure. In order to fulfil this part, it has been kept in mind some requirements listed below.

- Changing the specimen safety – When user needs to remove or introduce a specimen, it has to be safe enough to prevent any user injury.
- Releasing system – The releasing system has to be trustworthy enough to keep the hammer even though under machine movements.

Another important requirement is that the machine should be able to test all these materials, then it need enough energy to brake all of them.

Table 4 Energy required for the hammer

Material	Impact strength (J/m)	Impact strength (J/m^2)	Energy to deliver (J)
RGD 515, 535, 531	65-80	6398-7874	0.205-0.252
RGD 525	14-16	1378-1575	0.044-0.050
RGD 720	20-30	1969-2953	0.063-0.094
RGD 810	20-30	1969-2953	0.063-0.094
RGD 850, 875, 835, 836, 841, 851	20-30	1969-2953	0.063-0.094
RGD 840	20-30	1969-2953	0.063-0.094
RGD 430	40-50	3937-4921	0.126-0.157
RGD 450	30-35	2953-3445	0.094-0.110

The impact strength data was from a document and it was given using the ASTM 256-06 standards. In that document it is shown that the width of the specimen is 12.7 mm however, it is just 10.16 mm in the section of the notch. That means that the energy per square meter is the value divided by 0.01016 m. The specimen in SFS-EN ISO 180 has a section of 8 mm by 4 mm in the notched section. Then, the energy that the hammer needs to deliver is

$$E > \frac{8 \cdot 4 \cdot I_s}{1000 \cdot 10.16}$$

This is the energy needed from the pendulum to deliver against the specimen.

3.1.2 Standards requirements

In the standards there are lots of requirements and they will be listed and explained below. It is really important to follow these requirements in order to have a standard machine and being able to compare the results. Also, some of them are given to avoid common mistakes when building those kind of test machines. First of all, the machine requirements.

- Mass of frame – The mass of the frame has to be at least 40 times heavier than the pendulum and has to be bolted to a rigid test bench.
- Centre of percussion of the hammer – The centre of percussion in the hammer has to be ±2.5 mm at the line of strike.
- Axis of rotation of pendulum – It has to be parallel within ±2/1000 relative to the reference plane.
- Plane of swing – This must be perpendicular regarding the axis of rotation of the hammer.
- Axial play of axis – The endplay of the pendulum bearings in the axial direction cannot exceed 0.25mm.
- Radial axis play – This movement should not exceed 0.05mm in the radial direction when 2±0.2 N is applied in different directions perpendicular to the plane of swinging.
- Holding and releasing mechanism – This mechanism shall release the pendulum without initial impulse, retardation or side vibration.

- Free hanging position – When the pendulum is hanging free, the striking edge shall be within 6.35±5.00mm of the position where it would just touch the reference specimen.
- Contact between specimen and striking edge – The striking edge should make contact over the full width of the specimen.
- Potential energy – The potential energy for Izod test machines shall not differ by more than 1% of these nominal values (1, 2.75, 5.5, 11 and 22 J). Moreover, when testing, it is important that the energy absorbed by the specimen is between 10 and 80% of the energy delivered. If there are two standard hammers that can do that always use the one which gives more energy.
- Impact velocity – The speed of the striking edge in the impact moment shall be 3.5(±10%) m/s.
- Losses due to friction without specimen – The losses must not exceed these values depending on the nominal potential energy respectively (2, 1, 0.5, 0.5, and 0.5 % of the nominal value).
- Radius of striking edge – The striking edge of the hammer shall have a cylindrical surface with a radius of 0.8±0.2 mm, with its axis perpendicular to the plane of the motion of the pendulum.
- Parallelism of clamp faces – The horizontal and vertical faces of the both clamps shall be parallel.
- Radius of support block – The support clamp block shall have a top edge with a radius of 0.2±0.1mm.
- Pendulum length – The pendulum length should be between 225 and 390 mm.
- Height of striking edge – The striking edge shall be 22±0.2 mm over the top surface of the clamp.
- Top surface clamp – The top surface clamp should be horizontal within ±3/1000.
- Side surface clamp – The angle between the support and clamping blocks and the top surface of the clamp has to be 90±0.5º.

Even though there are more requirements listed in the standards, these are the most important and it is not necessary to list the others, it is just important to fulfil them when building the machine.

3.2 Designing

For the designing of this Izod test machine has been used the software SOLIDWORKS. For this project has been used the subassemblies method. This method consist in designing the parts with the idea that the engineer has in mind to assembly everything. After making the final assembly of all the parts, the whole system has to be divided in some subsystems and if necessary, those in other subsystems (in this project it was not needed). Afterwards, the assembly should be done using almost only the subassemblies. In this way everything is clearer and it is easy to solve the issues and make changes.

It is also important to name the archives with clear and smart names to have them ordered. The system used in this project is simple, there are something like XX.00.000.00. The first “XX” are two letters referred to the subsystem, for example, the hammer releasing system is “HR”, and so all the parts of this subsystem will have those letters. The two next numbers designate the level of the archive, level 1 is a part, level 2 is a subsystem and level 3 should be the system. The next three numbers appoint the number of the part, if it is the first or the second piece. The last two numbers are the version of that archive.

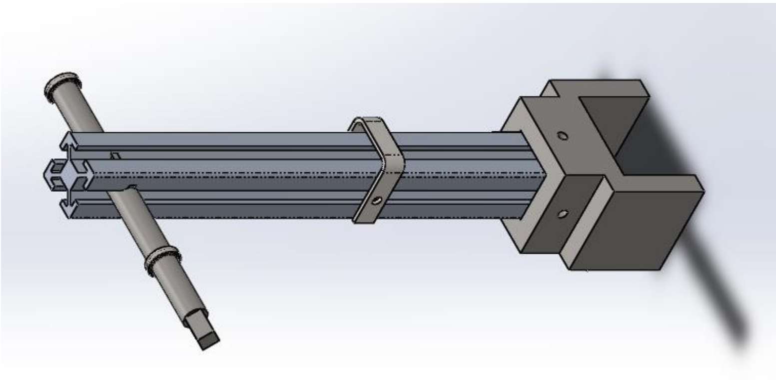
Furthermore, in each folder of subsystems there is another folder named “old”. This is where all the old versions are saved in order not to lose any design even though it can seem useless, they are arranged by the last number (version number).

In this chapter, is shown all the versions of each part of the machine, however, most of the irrelevant pictures will be in the Annexes.

3.2.1 Hammer (HA)

The hammer is the most demanding part of the machine, almost all of the standards requirements depends on the hammer design. The most significant of them are the centre of percussion, the energy delivered and the speed in the striking point. Also, there is a procedure rule that states that the energy absorbed by the specimen should be between 10 and 80% of the hammer total energy.

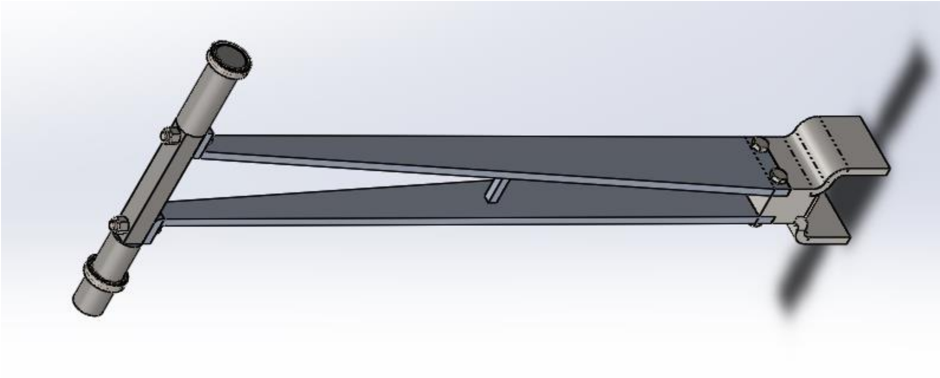
The first design of this part tried to use an aluminium profile similar to the one used for the frame. It had a cylindrical axis and the profile had a hole to introduce the axis. The transmission of the movement was thanks to a split pin on the axis. The striking part was fastened using bolts and t-nuts in the profile. The striker was made with an extruded piece of aluminium welded to two aluminium sheets that gave that shape shown in the picture below. And there was also a piece bolted in the middle of the arm to hold with the hammer keeper.



Picture 2 First design of the hammer

This design was really good due to the building and manufacturing ease. The only problem was that it was impossible to achieve the centre of percussion issue. This is one of the worst problems of this kind of machines, changing the centre of percussion is a really difficult task, even more considering that the mass should not change a lot. With this arm, the centre of percussion was too close to the axis of rotation, so it was needed a design with more inertia but less mass, and the only way was making the arm lighter.

The second design was made using two metal sheets bent as the arm, welding a squared profile to make it stiffer. This small profile was also used for holding the hammer with a new design of the hammer keeper. The axis had a squared part to affix the arm with bolts and nuts, this made easier to change the hammer. The striker part is made by a central prism part of steel welded to two bent sheets of steel. The striker was easily fasten to the arm with 4 bolts.

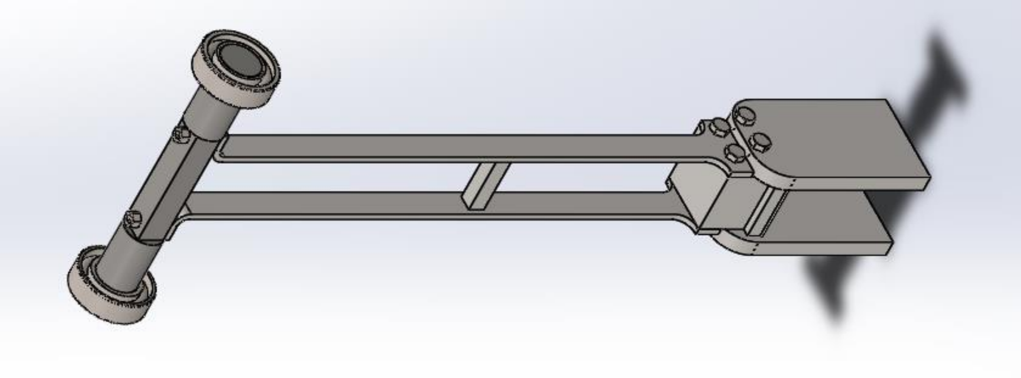


Picture 3 Second design of the hammer

This was a really good design because the centre of percussion was pretty close to the centre of strike. Furthermore, it was easy to move the centre of percussion and allocating it in the right place. However, the really worrying problem was that the arm was made by a sheet of 5mm of aluminium. Aluminium is a good material and widely used due to its high resistance and ease to manufacture. However, this material is so ductile, which means that with this kind of impacts repeatedly would be bent owing to the fatigue. The reason to make it of aluminium was because it needed to be very light in comparison with the striking part.

The striking part was also pretty difficult to produce on account of the sheet bending and the striking edge that have the requirement of 0.8±0.2mm of radius, something really difficult to make. For these reasons the design was modified anew.

The third design was completely made of steel owing to its incredible mechanical properties. Making the arm with this material the weight was highly increased, so the shape was significantly changed to reduce the weight to the limit. The striking part now was composed by two thick sheets of steel and a 3D printed part of steel with the striking edge and four holes to attach to the central part. The central part is just a cube plenty of threaded holes to unite all the parts with bolts. Moreover, the axis diameter was increased to get more resistance in the arm part.

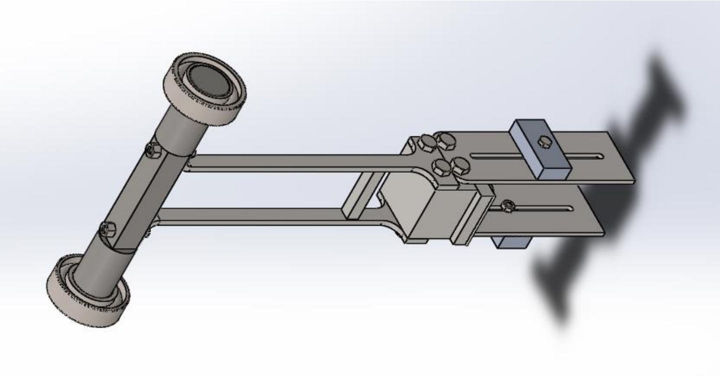


Picture 4 Third design of the hammer

This was the best design of the hammer achieved. It is the easiest to build because almost all is made by profiles, sheets and an extruded cube (the most difficult). The high resistance and tenacity makes this the best design.

Although the third design was really good, it did not fill the energy requirement of the costumer. This was made for 11 J of energy delivered while the costumer need between 0.044 and 0.252 J. So, this hammer had too much energy because the 10% of it would be 1.1 J. However, the lightest standard hammer would be only able to deliver 1 J so the measurements for the weakest plastics would have a less precise measurement.

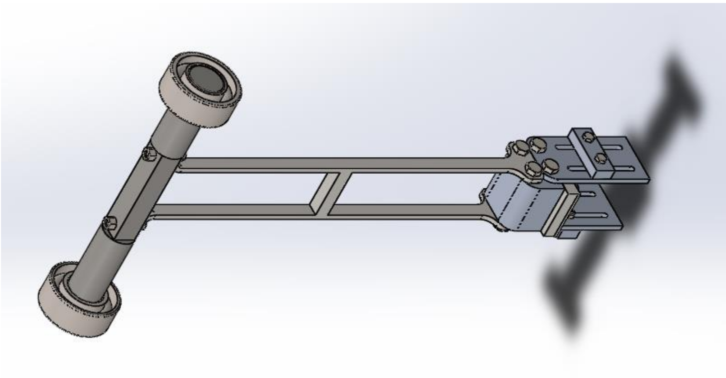
For the fourth design it was tried to reduce considerably the energy delivered and this design was able to deliver until 2.75 J despite the fact it was not possible to get 1 J. This design was pretty similar to the last one but was really shorter and it had two aluminium pieces to calibrate the machine. All of it was made of steel and the length of the pendulum was 225 mm which is the lowest limit given by the standards. The two sheets in both sides of the striking edge were so long to give more inertia in order to put the percussion centre closer to the striking edge.



Picture 5 Fourth design of the hammer

This design really fulfil all the requirements, however there was one that it was not able to reach. The problem reducing the length of the pendulum is that the speed of the points closer to the axis are lower even with the same angular speed, so the striking edge was not able to reach the 3.5 m/s.

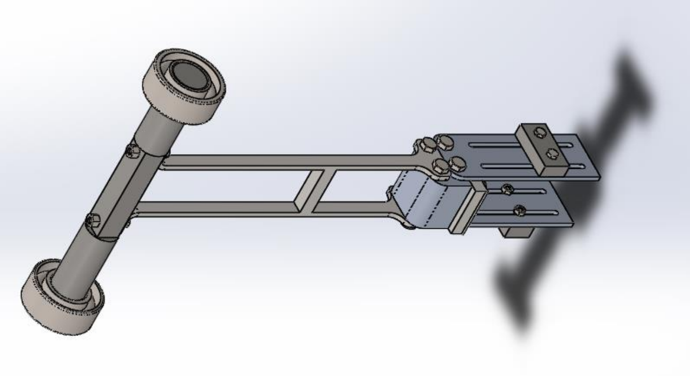
The fifth hammer design was quite longer than the fourth. The union part and both fins were made of aluminium to reduce the inertia, trying to get the 2.75 energy hammer. Also, some parts were given a round shape to reduce the weight. Besides, both counterweights were provided with an additional rail to restrict the movement.



Picture 6 Fifth design of the hammer

In spite of the effort utilised to make this design functional, it was almost impossible to achieve all the requirements at the same time owing to the centre of percussion was not on the line of the striking edge.

For that reason, it was decided to focus on the problem from another point of view. Digging deeper within the equations it was found a solution. Far from being the best design, the sixth was the only one which got to fulfil all the requirements. Even though the similarities between this and the design before, there has been more changes than the length of the arm.



Picture 7 Sixth design of the hammer

This is the final design for the arm which is able to abide by all the requirements.

The most important calculus made in this subsystem were the centre of percussion, the energy released and the speed in the impact point. The procedure and the calculus made to develop the hammer design is explained below.

As it has been explained before, the equation to calculate the centre of percussion is the following:

$$l_{CP} = \frac{I_0}{m \cdot l_{CG}} \ (1)$$

The equation for the potential energy would be something like this:

$$E_P = m \cdot g \cdot h_{CG} \ (2)$$

The next equation is the kinetic energy formula.

$$E_K = \frac{1}{2} \cdot I_0 \cdot \omega_{CG}^2 \ (3)$$

The last equation needed is the conservation of energy without taking into account the energy losses. Having in mind that kinetic energy in the releasing point and the potential energy in the lowest point are 0,

$$E_K - E_P = 0 \ (4)$$

It is possible to see a compound pendulum in the figure below, where the 0 reference for the energy equation is the horizontal crossing the point CG’.

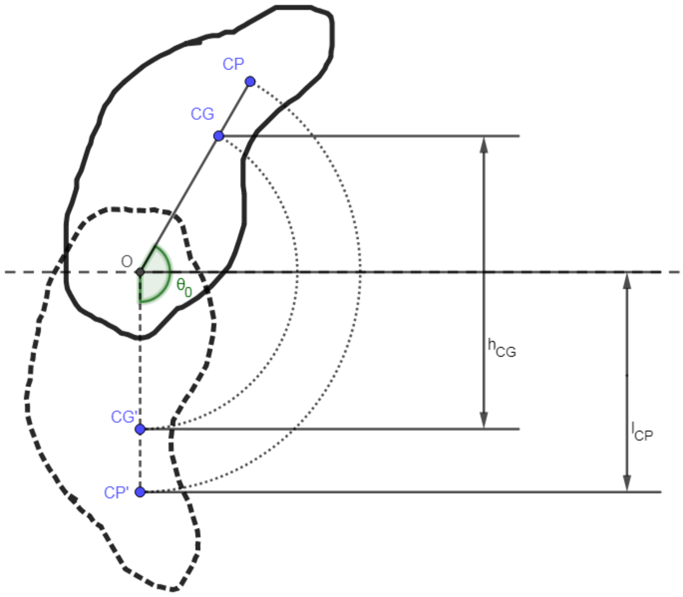


Figure 6 Compound pendulum scheme

Using this, it is easy to deduce the relation between the gravity centre height and gravity centre length.

$$h_{CG} = l_{CG} + l_{CG} \cdot \sin(\theta_R) = l_{CG} \cdot (1 + \cos(180 - \theta_0)) \ (5)$$

Now, introducing (5) in (2), and (3) and (2) in (4), there is the following:

$$\frac{1}{2} \cdot I_0 \cdot \omega_{CG}^2 = m \cdot g \cdot l_{CG} \cdot (1 + \cos(180 - \theta_0))$$

Also, knowing that the angular speed is

$$\omega_{CG} = \frac{v_{SE}}{l_{CP}}$$

$$\frac{1}{2} \cdot I_0 \cdot \left(\frac{v_{SE}}{l_{CP}}\right)^2 = m \cdot g \cdot l_{CG} \cdot (1 + \cos(180 - \theta_0))$$

The term $m \cdot l_{CG}$ from (1) can be included to have the length of the centre of percussion

$$\frac{1}{2} \cdot I_0 \cdot \left(\frac{v_{SE}}{l_{CP}}\right)^2 = g \cdot \frac{I_0}{l_{CP}} \cdot (1 + \cos(180 - \theta_0))$$

With this, the inertia is divided and it is demonstrated that the centre of percussion and so, the length of the arm can be found without the inertia. Solving the equation for the length of percussion centre,

$$l_{CP} = \frac{v_{SE}^2}{2 \cdot g \cdot (1 + \cos(180 - \theta_0))}$$

As said in the requirements, the speed has to be 3.5(±10%) m/s, so 3.5±0.35 m/s and the angle can be between 120 and 150 degrees. As seen in other designs, the longer the arm was, the more difficult was to fit the centre of percussion. That is why here it was chosen

150 degrees and, going to the limit 3.15 m/s. This was the only way to fulfil the requirements. So, the centre of percussion should be

$$l_{CP} = \frac{3.15^2}{2 \cdot 9.81 \cdot (1 + \cos(180 - 150))} = 0.2710\ m = 271.0\ mm$$

Using the equation (1) and (2) with (5) it is possible to know the inertia.

$$E_P = m \cdot g \cdot \frac{I_0}{m \cdot l_{CP}} \cdot (1 + \cos(180 - \theta_0))$$

The mass is divided and in this case the potential energy should be 2.75(±1%) J, so 2.75±0.275 J and the centre of percussion is already known.

$$I_0 = \frac{E_P \cdot l_{CP}}{g \cdot (1 + \cos(180 - \theta_0))} = \frac{2.75 \cdot 0.271}{9.81 \cdot (1 + \cos(180 - 150))} = 0.0407\ kg \cdot m^2$$

The inertia of the designed hammer is 0.0410 $kg \cdot m^2$ so is really close. To calculate the mass and the centre of gravity there is no equation, but it is possible to find a relation between them using (1).

$$m \cdot l_{CG} = \frac{I_0}{l_{CP}} = \frac{0.0407}{0.2710} = 0.150$$

The mass of the current hammer is 1.3815 kg and its gravity centre is 0.1102 m from the axis.

$$1.3815 \cdot 0.1102 = 0.152$$

This is also pretty close to the value expected. Looking in to the real values, the energy delivered is

$$E_P = m \cdot g \cdot l_{CG} \cdot (1 + \cos(180 - \theta_0))$$
$$= 1.3833 \cdot 9.81 \cdot 0.1104 \cdot (1 + \cos(180 - 150)) = 2.787\ J$$

It is in the error accepted. The centre of percussion is

$$l_{CP} = \frac{I_0}{m \cdot l_{CG}} = \frac{0.0410}{1.3815 \cdot 0.1104} = 0.269\ m = 269.37\ mm$$

Which is also in the error of ±2 mm. Finally, the speed in the contact point is

$$v_{SE} = \sqrt{2 \cdot l_{CP} \cdot g \cdot (1 + \cos(180 - \theta_0))} = \sqrt{2 \cdot 0.269 \cdot 9.81 \cdot (1 + \cos(180 - 150))}$$
$$= 3.16\ m/s$$

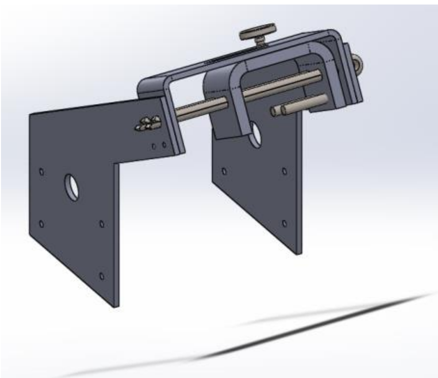
This value is also in the error accepted. So this is the final design, the number six has reached all the requirements even though it has been quite difficult.

3.2.2 Hammer releasing system (HR)

This subsystem was the one which required more creativity. Despite the fact that there are some requirements and it is really important there was not only one possible design.

There is only two important requirements to follow here. The first one is that it has to be secure, that is, the releasing system should be able to release the hammer but also to hold it in the highest position without chance to fall by mistake. The second condition is that the hammer should not vibrate due to the releasing action, meaning it shall drop it without unnecessary hit.

The first design made for this system was compound by four metal sheets, two of them bent. The idea of this system was using standard parts and some sheets to have a cheap system, reliable and easy to assembly. The two sheets on both sides were assembled directly to the frame with bolts. Those two long screws were holding another bent sheet tightened to the hammer arm. The split pins were used as trails and the knurled screw was to make it more comfortable than moving a simple bolt.

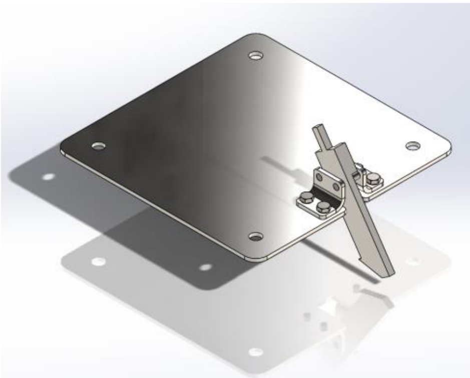


Picture 8 First design of the hammer releasing system

This design was a really good idea bearing in mind that it was the first concept. Nevertheless there were a lot of issues that needed to be fixed. The first issue was the amount of material needed just to hold the hammer. The second problem is that probably the movement of the holding part along the trails would generate vibration and this is one of the requirements it shall fulfil. In addition, the screws holding the hammer, probably would generate more vibration which means more energy losses. Besides, leaving the arm from one side could generate a lateral movement or, at least stresses.

Although it was easy to assembly and it was really trustworthy, for all that reasons, the system needed a change. The next idea was reflected in the second design shown below.

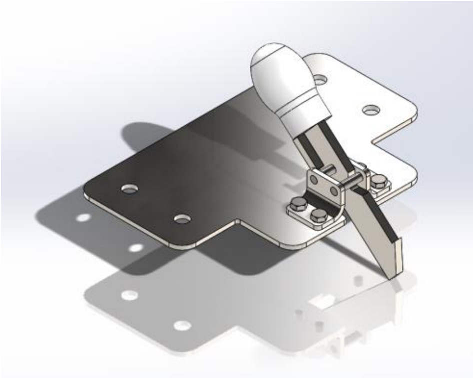
The second design was a whole change from what had been thought until then. The trail system was substituted for a rotational system with just 3 metal sheets and two axis. The rotating part was holding the hammer with just a little tab and this reduce the vibrations. Furthermore, the sheet increase the stiffness of the structure.



Picture 9 Second design of the hammer releasing system

As said before, this design reduce the vibration energy losses because it is needed just a small movement to release the hammer. Additionally, there is no torsion in the hammer arm given that the releasing system is moving in the plane of the swinging arm. Despite these good points, this releasing system is not secure enough. It is likely that the hammer is released by some movement of the machine. Any little disturbance could release the arm and this is not admissible.

Therefore this design was modified. Surprisingly, it was not necessary a huge change considering that it was necessary to turn the holding part over. In this way, when the hammer, which is producing a force down (because of the weight), pretends to drop, the hammer holding will block the movement if nobody levers it.



Picture 10 Third design of hammer releasing system

This system is not only more reliable and safe, but also more comfortable due to the ergonomic design. The sheet is smaller in order to save unnecessary material and the shape was changed in order to adjust it better to the structure. The notch added in the holding part will give the necessary trajectory in the way that it is not necessary to touch the lever when lifting the hammer to hold it.

Here there was an important calculus for the torsion spring needed in this system. It was important to find a suitable torsion spring for this system. The spring had to be strong enough to withstand the torque in the maximum angle needed to release the hammer. But it also needed an initial force to uphold the holding part.

The angular movement of this part is so small, but it is important to have the spring well tautened giving a margin in order not to brake the spring. The mass centre of the lever is near to its axis so it will not count on its weight.

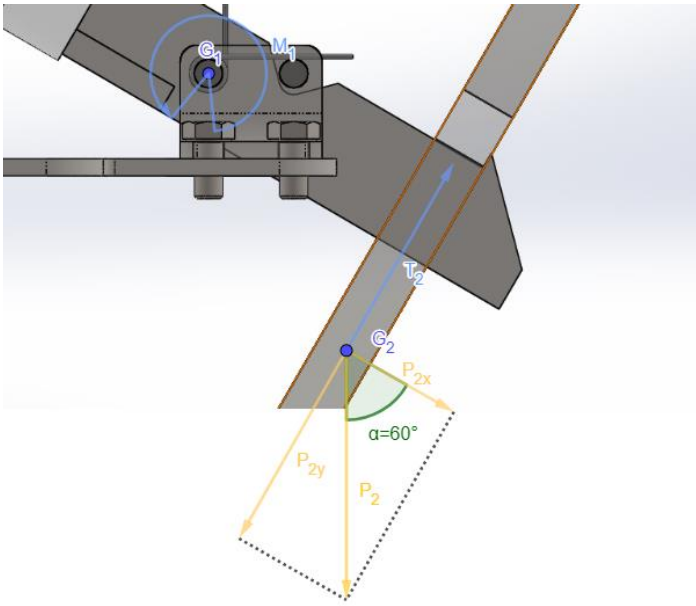


Figure 7 Forces in hammer holding scheme

In the scheme above it is appreciable the two components of the weight of the hammer. The vertical component (which goes along the arm) is countered by the reaction in the axis of the hammer so it does not generate forces in the hammer releasing system. The second part of the force is cancelled out by another reaction in the axis of the holding system. However, this force is applied over the tab of the holding system. The distance, perpendicular to the action of the force, from the tab (application point) to the centre of rotation of the releasing system is 10 mm. Consequently, this force generates a momentum, so the momentum generated by the spring should be bigger than this one. To calculate it is going to be used one simple equation that states that the force of a particular weight is

$$P_2 = m \cdot g$$

In this case, the component needed is in the x direction and the momentum is the force by the perpendicular (to the force direction) distance between the centre of rotation and the application point of the force, so

$$P_{2x} = P_2 \cdot \cos(\alpha)$$

$$M_1 = P_{2x} \cdot 0.01$$

Then, the momentum needed for the spring will be

$$M_1 = m \cdot g \cdot \cos(\alpha) \cdot 0.01 = 1.3815 \cdot 9.81 \cdot \cos(60) \cdot 0.01 = 0.0678\ Nm$$

The force that the spring needs to apply over the furthest point (25 mm from the axis) is, at least,

$$F_1 = \frac{M_1}{0.025} = \frac{0.0678}{0.025} = 2.71\ N$$

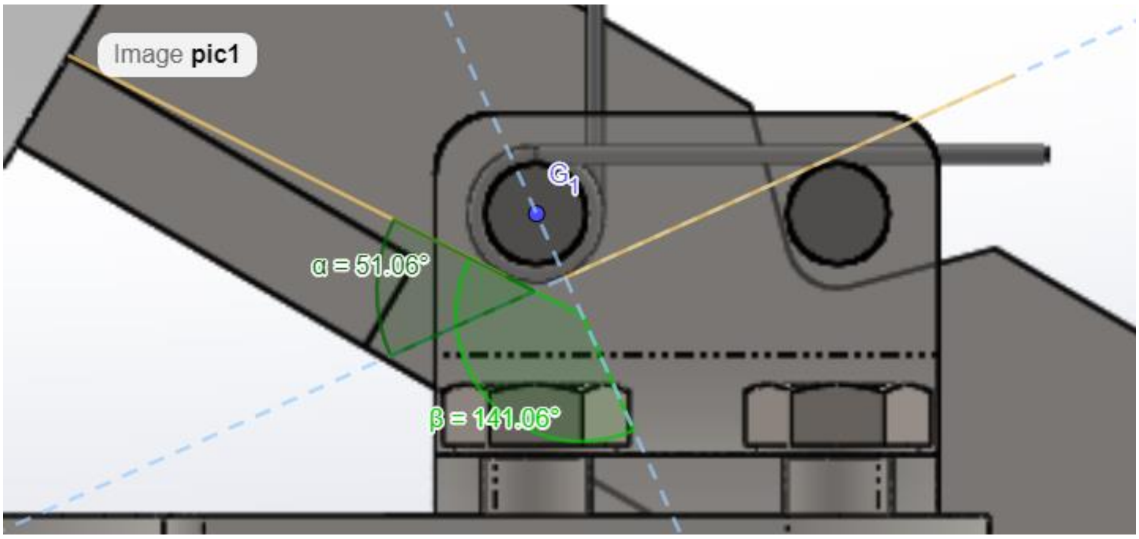


Figure 8 Angle of torsion of two kind of springs

In this image it is possible to see the initial angle of torsion of two kind of springs. So the spring chosen should be strong enough to make more than that force. The one selected can deliver 10 Nmm/deg. which means that would be able to give a force of

$$F_1' = \frac{0.01 \cdot 51}{0.025} = 20{,}4\ N$$

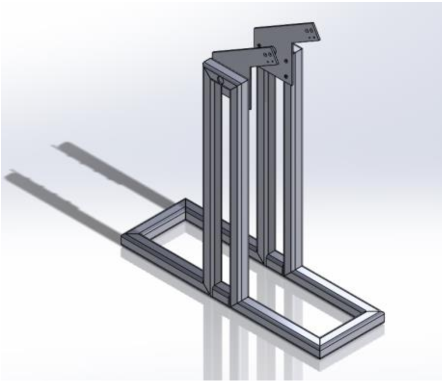
So this force is enough to hold the hammer. And it is secure enough.

3.2.3 Structure (ST)

The structure is one of the most important parts. Notwithstanding that is not something difficult to design, it is the basis of every machine, even more for measurement machines. If the structure is not good enough, the machine it will not be as precise as it could have been. Also, is the most important part of the security, and being safe is the first. The structure shall be though, stiff and strong enough to withstand all the stresses that can be produced by the machine or, if that were the case, by outside influences.

It is also important that anything wanted to be assembled in the machine could be easily affixed. As it has been seen in the requirements it needed to be heavy enough so, the structure can be done with a heavy substance or it could be done with any material and joined to a heavy part as a foundation.

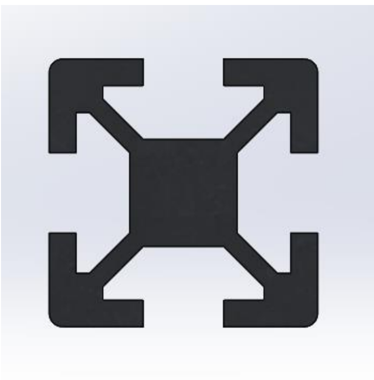
The first design was made by a profile made of steel. The rectangular profile was a really heavy material so it was not necessary to build a foundation. In addition, the profile was welded, and so the need of ordering fastening parts disappeared. The idea to assemble all the parts was making some threatened holes to the structure and screwing the bolts.



Picture 11 First design of the structure

The good part of this design was that not one foundation was needed because of the high weight of the steel. Furthermore, steel is one of the strongest metals used in the industry and it should have been stiff enough. The problem was that it required too much welding, it could be too expensive and it would not be adjustable.

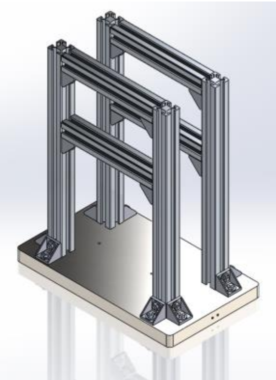
In consequence, the steel was substituted by aluminium which is much more versatile for any use. The aluminium profile usually have a shape similar to the picture below



Picture 12 Typical aluminium profile

This sort of profiles usually are attached using T-nuts[27] and bolts. Introducing the T-nut through the profile cavity it is possible to use it as if there were a hole across the profile and a nut in the other way. The best advantage of this is that there is no need to drill the profile to fasten any piece.

The second design was made with this aluminium profile using angles[28] and T-nuts to fasten the profile parts. The T-nuts were also used to attach the other parts to the structure. Firstly there was an idea to make the same shape of the first design and add a steel, cement or any other heavy material in the base. However, it was classified as a bad concept. Finally was thought that the best for the foundation would be utilising a table as a heavy basis, the same table where it is going to be used.



Picture 13 Second design of the structure

In this system is possible to change the height and the position of the beams in order to calibrate the machine.

The most important calculus in this subsystem is the resistance of the structure and the possible movement or bent of the different girders. To start is important to know what are the maximum forces applied on the structure. The fictitious forces equation should be used to know this as

$$F = m \cdot \dot{\omega} \cdot r\ (\hat{\theta}) + m \cdot \omega^2 \cdot r\ (\hat{r})$$

[27] A kind of nut shaped like the head of a T. It is usually inserted in a metallic profile to assemble parts on the profile.
[28] Part with a shape of a right-angled triangle extruded. It is used to assemble two parts perpendicularly.

The mass is the mass of the hammer, the radius is the gravity centre and the speed and acceleration are changing depending on the position. In order to know the maximum fictitious force it has been used excel and made two graph that provides enough information to know the angles where there are more fictitious forces.

The first chart represents the angular acceleration and the square of the angular speed versus the angle position of the pendulum.

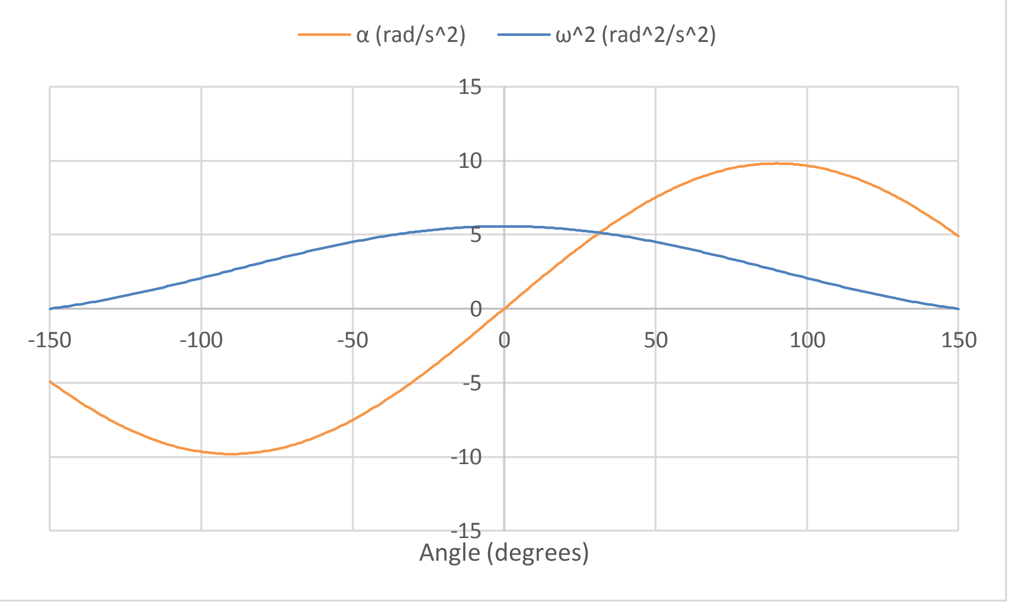


Figure 9 Chart of angular acceleration and square of angular velocity versus pendulum angle position

The second graph represents the fictitious force in absolute value versus the angle again.

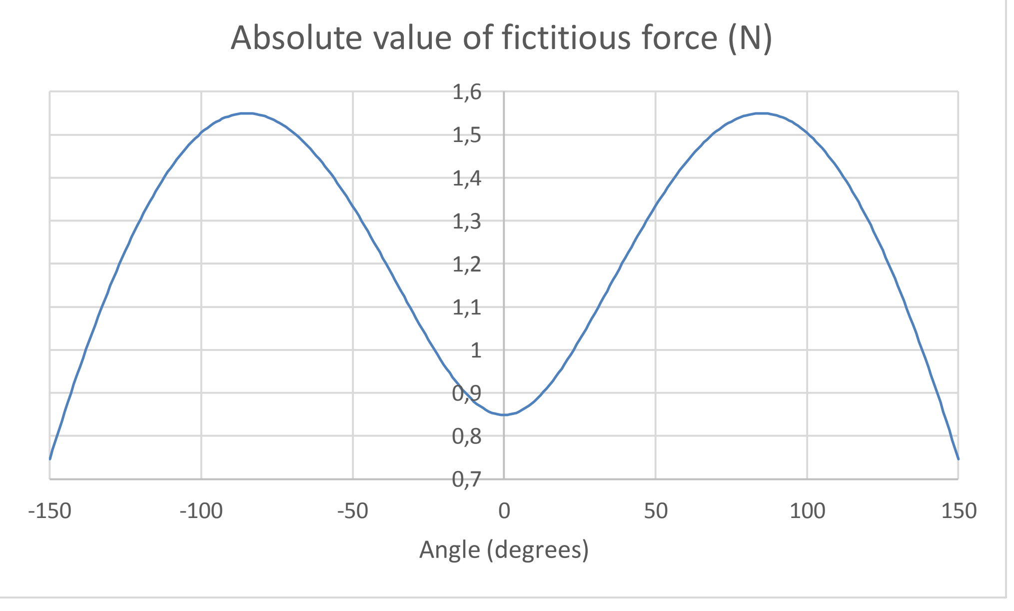


Figure 10 Chart fictitious force in absolute value versus the angle

From the second graph and looking the results in excel it is possible to say that the highest force is around ±85 degrees. However, it is important to remember that this is representative and the fictitious force in this chart is in absolute value. Looking at the first graph, it is possible to see that the sign of one component is different, but that means that the modulus of that force vector is the same but just change the direction, in this case it is symmetric because it is the same height. Now it is possible to calculate the forces in the angle 85 degrees, so it would be something like this:

$$F = mg \cdot \sin(85) \cdot r\ (\hat{\theta}) + m \cdot \left(\sqrt{2 \cdot mg \cdot r \cdot (1 + \sin(60) - 1 + \cos(85))}\right)^2 \cdot r\ (\hat{r})$$

Solving this in both directions radial and tangential, there is left

$$F(\hat{\theta}) = m \cdot g \cdot \sin(85) \cdot r = 1.3815 \cdot 9.81 \cdot \sin(85) \cdot 0.1102 = 1.488\ N(\hat{\theta})$$

$$F(\hat{r}) = 2 \cdot m^2 \cdot g \cdot r^2 \cdot (\sin(60) + \cos(85))$$

$$= 2 \cdot 1.3815^2 \cdot 9.81 \cdot 0.1102^2 \cdot (\sin(60) + \cos(85)) = 0.433\ N\ (\hat{r})$$

The absolute value of this is

$$F = \sqrt{1.488^2 + 0.433^2} = 1.550\ N$$

Even though is a relatively low force, it is needed to make the development to be sure that there is not a failure in the structure. To make it easier, it has been used the software MEFI for structures calculus. It has been applied 15N in vertical and 0.3N in horizontal which is the force in 85 degrees plus the force of the weight of the hammer. Even though the force is the half because the hammer is held by two of these structures it is interesting to see that the deformation is small enough.

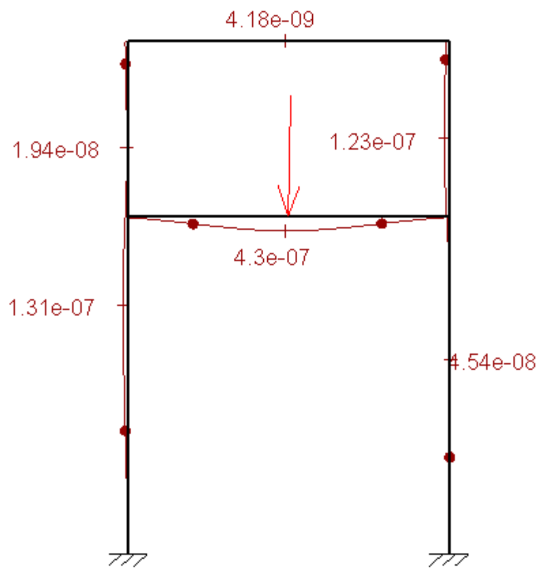


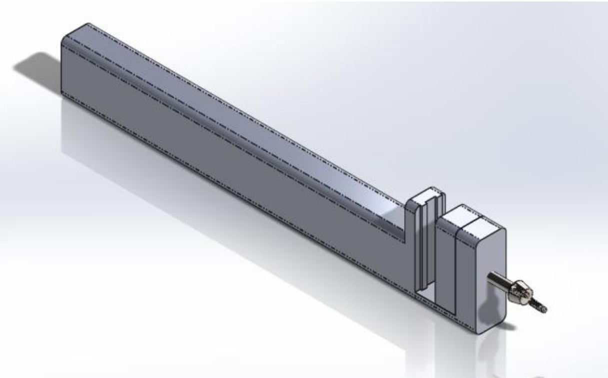
Figure 11 Diagram given by MEFI using the structure of this system and al the information of the materials used

This software is also able to calculate the stresses in each beam. So it is possible to know that the maximum stresses are in the central rafter in both sides as expected. However, it is way too weak to brake it or even to generate strains. So the structure is strong enough to withstand all the loads and stiff to avoid vibrations as well.

3.2.4 Support/Clamping block (SU)

This subsystem does not requires lots of parts and it has not too much requirements from standards, however, is not so easy to design and manufacture it. The most important in this part is that the support block shall withstand all the impacts given by the hammer that are transmitted directly from the specimen.

As said, it has to be so stiff and well attached to the frame in order not to have unnecessary movements. Consequently, the first design was made with the same profile of the first design of the frame. This is strong enough and every part could have been made of steel.

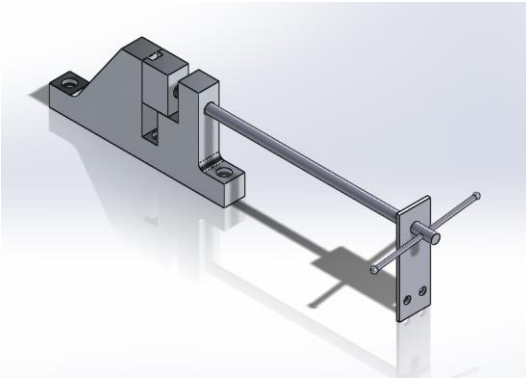


Picture 14 First design of support and clamping blocks

Apart from the change made on the frame, this design needed to be modified because it would have been so difficult to produce and join all the parts together. Even though it could be a good solution, it was not possible to make it real.

For that reason, the second design was made. It is necessary to say that this design was changing to arrange to the other subsystems. Nevertheless, the basis of the concept of this design have never changed until then. Some changes were also due to the difficulty to make, some others were in order to increase the resistance of this part.

This design is made with a central part of aluminium and a clamping block made of aluminium as well. The good part of this design is that it can be affixed wherever because is just one part and it does not depend on the frame because is fastened to the foundation. The threaded axis is made of steel and it has a small diameter stick to generate momentum enough without too much effort. The metal sheet made of aluminium on the other side of the axis is to avoid the bend. The support block is affixed to the foundation with three screws that will avoid the movement of that block.



Picture 15 Second design of the support and clamping blocks

This is a really good design made of aluminium. One really important part is the top left edge of the support block that is in contact with the specimen. In the requirements it is said that it must have a radius of 0.2±0.1mm. Thus that part cannot be made with whichever method, it has to be precise enough and the part was really thick to make it with laser cutting. However, it was possible to change the width and, despite the fact that was not even possible to cut 20mm with laser, it was possible to do it with waterjet method that is going to be explained in the next chapter.

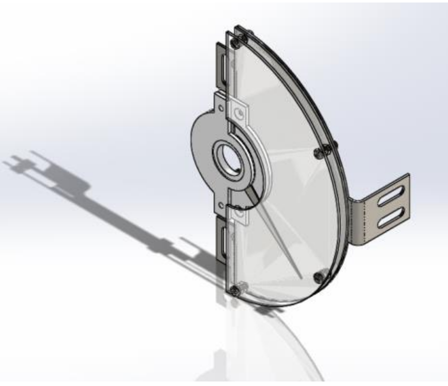
3.2.5 Measurement system (MS)

This system is the interface with the user, this is something that the user is going to be looking every time, so it should be aesthetically pleasant, though is not the most important. The essential in this subsystem is the accuracy, the system has to be accuracy enough in harmony with the rest of the machine like the hammer. If this system have a bad accuracy, the effort made in other systems will be worthless.

The most challenge in this part is maintaining the pointer in the last position reached by the hammer. The problem here is that it cannot have too much friction but it needs some friction to stay. Furthermore, there is a problem to attach it to the frame because the axis is quite far from almost all the parts of the frame. It is also difficult to make a part that is rotating in the same axis of the hammer but separating the movements.

First of all it was thought to do this with electronics, but due to the lack of time it was not possible. So, the measurement is made in the traditional way with a simple mechanical system. There is a pointer that is moved by another part which is connected to the axis of rotation. The pointer cannot be connected directly to the axis otherwise, the pointer would be moving after braking the specimen and it would be impossible to take a measurement.

The first design made was thought to have a basis of sheet of steel bent in order to fasten it to the frame. There was also a layer made of methacrylate and between them, there is a printed paper with the scale, this is for avoiding the scale damaged and if something is wrong it can always be changed. The third layer is also made of methacrylate and this is to separate the pointer from the outside. This last part maybe could be removed but it gives a nice look. Besides, there are two parts made of ABS 3D printed to make a little pressure over the pointer that is also made of steel.



Picture 16 First design of the measurement system

This is a nice design and it can be calibrated easily with two screws that changes the pressure on the pointer.

3.2.6 Whole machine

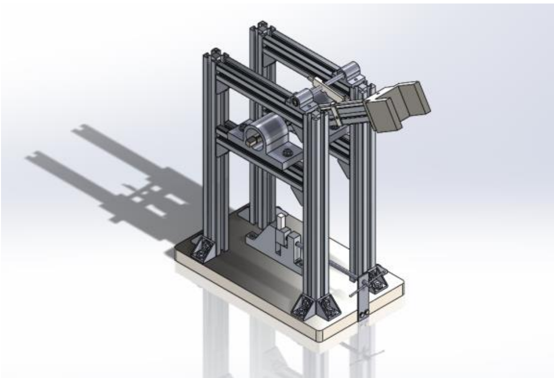
The machine has been changing during the process, due to the changes in each subsystem. Here is exposed a brief explanation of the different designs because the changes have already been clarified in the points above.

The first design was with the steel frame and the arm was made also with the same steel profile. This was not considered the first hammer design because it was done without having in mind the requirements, so was made as an example. The releasing system was the first also and here is noticeable how it worked.

Picture 17 First design of the pendulum machine

However, this design still needed to fill all the requirements.

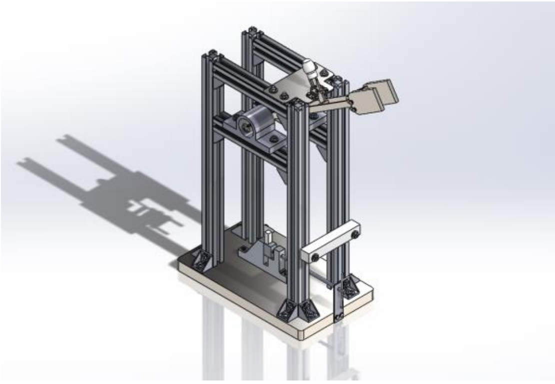
In the second design, it was used the frame of aluminium and the arm was done with the same idea. The releasing system changed as well, but it was not secure enough as can be seen.



Picture 18 Second design of the pendulum machine

This design was quite more proportional but was still not keeping to the requirements.

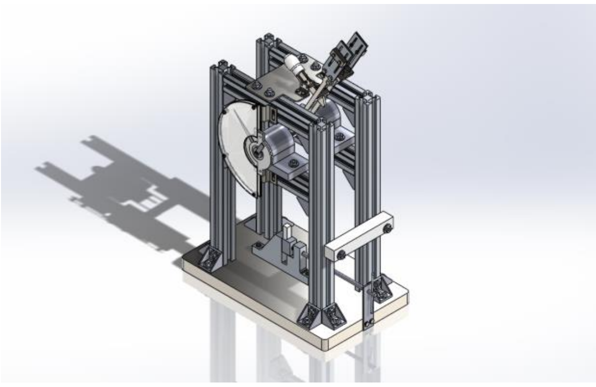
The third design was really better and it included the security system which is used to change the specimen in order to avoid damages. The releasing system was also improved and it had a better grip with the hammer.



Picture 19 Third design of the pendulum machine

The only problem here was that this machine was designed to deliver 11 J when the materials to test just needed about 3 J. Also there was left the measurement system.

Finally, with the fourth design, it was made a pendulum that fulfil all the requirements and also a way to calibrate it. The measurement system was also designed and attached and there was left to order the parts and assemble them.



Picture 20 Fourth design of the pendulum machine

This is the final design of the pendulum, there are included all the updates of every subsystem and there are a lot of calibration[29] systems.

[29] Set of operations that establish the relationship between measured values and the values corresponding to appropriate standards.

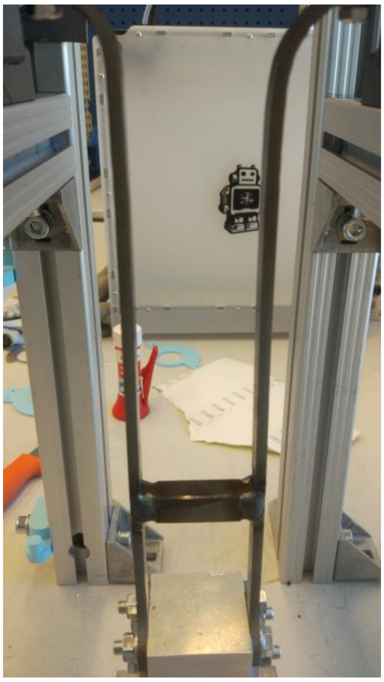
3.3 Manufacturing and ordering

For the manufacturing there were available some machines like welding gun, a lathe, a milling machine, a belt sander, an electric hacksaw, a drill press, and other tools to develop some parts of the machine.

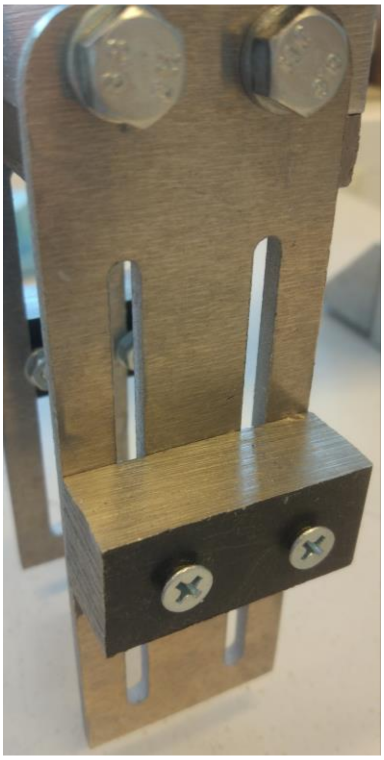
However, in this design there were pieces that needed to be ordered, some of them because there were not that material left, or because they required a special precision. Nevertheless, the budget for the ordering had to be under the thousand euros.

3.3.1 Hammer

For the hammer there are four parts made of metal sheet, two of them are made of aluminium with a thickness of 4 mm, and the rest are made of stainless steel and 4 mm as well. In the picture below they can be recognised.



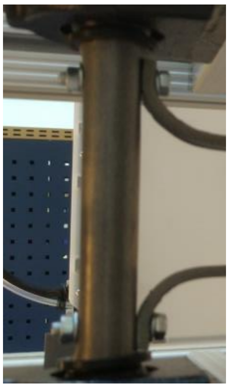
Picture 21 Arm of the hammer



Picture 22 Rail for counterweight

The piece in the first picture is one of the two parts of the arm of the hammer. It has two holes on the top and two on de bottom to assemble it to the axis and the striking part. The piece in the second picture is the part to attach the counterweight and calibrate the machine, so that is the reason for the slotted holes. These two parts were ordered in a laser company called “Tampereen Vesileikkaus Oy” and the two parts of the arm were bent by us.

There are also two profiles, one is for the axis of 25 mm of diameter made of stainless steel. This part has two holes to assemble the arm of the hammer and one axial threated hole for the piece which moves the pointer. The other part is the squared profile in the middle of the arm which is used to hold the hammer as well.



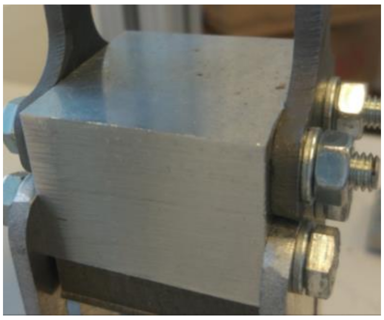
Picture 23 Axis of the hammer

Picture 24 Part to hold the hammer

The axis was made by a copper alloy and using the milling machine it was made the squared shape in the middle of the axis. Afterwards, the two holes were made with the drill press. The second part was a squared profile made of steel and filed in order to get a sharp edge because this part has to be hold by the releasing system which has a tab of 3 mm. This part was finally welded to both parts of the arm.

The other two parts are made with 3D metal printer (made of steel) and one made with a milling machine. The 3D printed part was done in this way because it was required a striking edge with a shape of a cylinder of 0.8 mm of radius, so it was the easiest way to do it. The other part is the basis of the rest of the pieces of the striking part, so this connects everything of the hammer.

Picture 25 Striking edge



Picture 26 Assemble part

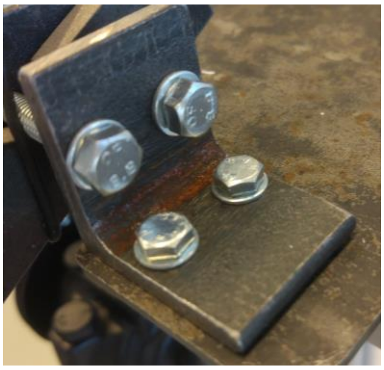
The first part was made with a 3D metal printer in Sastamala. The part of the second picture above has two holes for the arm and two for the counter weight rails. There are also four threated holes on the bottom for the striking edge. This part was taken from a aluminium cube. Was cut and filed until getting the right shape and size. Finally all the holes were made with the drill press and the threaded holes were made with a thread milling cutter. The holes needed to be very precise in order to avoid to be connected.

All those parts are screwed except for the squared profile which is welded to the steel sheets of the arm.

3.3.2 Hammer releasing system

The hammer releasing system has four parts made by laser cut of steel, two circular profiles, a spring and a plastic 3D printed part. The first laser cut part is the basis of the system is also used as a structural part to give more stiffness to the frame. This is a sheet with some holes to attach everything. The second one is bent and it has two holes to affix both axis, one for the holding part and another as a spring support.

Picture 27 Basis of the releasing system



Picture 28 Support for axis of the releasing system

The part of the second picture has a spotted hole to adjust the axis. The pictures below show the releasing part and the spring used to make the force to hold the hammer. The first part was ordered from the same company mentioned before. The second was taken from an L profile and it was pierced with the drill press.

Picture 29 Holding part

Picture 30 Lever handle

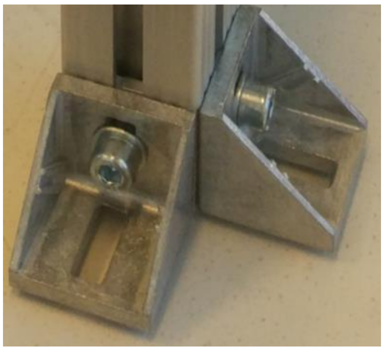
The part of the first picture is made of stainless steel of 5 mm which was ordered and it has a welded part of steel to make as support for the spring. The second picture is a 3D printed part to make the releasing movement more comfortable.

Then, all the parts of the hammer releasing system are already made.

3.3.3 Structure

The structure is basically made by aluminium frame and is attached using angles, t-nuts and screws M8. All those parts were standards and they were ordered in SKS group. The only machine needed for this was the electric hacksaw to cut the profile, the rest was assembled using screws. In the picture below it is possible to see the structure and the angles used to assembly it.

Picture 31 Structure



Picture 32 Angle

The whole structure is attached to the working table shown below.

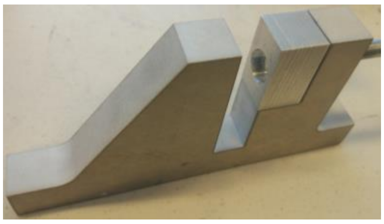
Picture 33 Working table

This subsystem does not have a lot of parts because the support system is considered another subsystem.

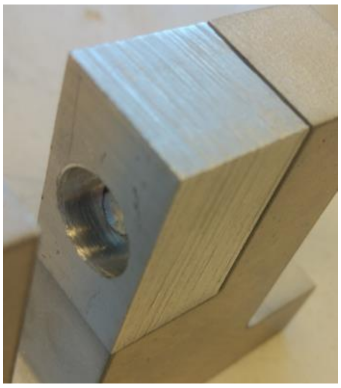
3.3.4 Support system

The support system has just four parts, a screw modified with a lathe, a 3D printed part, one laser cut part and one extruded part made with the milling machine. The technique used to cut the aluminium part of 20 mm was not laser cut but we called all the parts precisely cut with laser cut parts. The method used is named water jet cutting which uses a high-pressured jet of water with some abrasive substances to cut the material. This is able to cut relatively thick materials above 100 mm of thickness.

The laser cut piece is made of aluminium, is the support block and has a thickness of 20 mm. The part made with the milling machine is the clamping block. The first one has three holes to screw it to the foundation. The second one has one hole to introduce the threated axis which moves the support system.



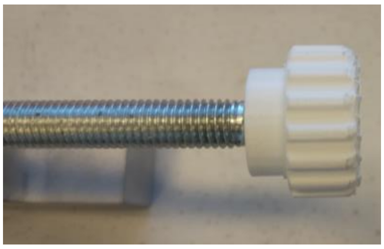
Picture 34 Support block



Picture 35 Clamping block

Both parts are made of aluminium and the first part has a rounded edge of 0.2 mm of radius on the top inner edge which is in contact with the specimen. The second part was made from an aluminium block cut and filed. Afterwards a hole was made in the back for the axis.

The last part is made using a M8 bolt attached to a knob with the shape of a hexagon made in 3D printer with ABS.



Picture 36 Axis with a knob for the clamping system

This part is an M8 screw with the last part as an axis of 6 mm of diameter using the lathe. The plastic part attached is a knob to do it easier affixing the specimen.

3.3.5 Measurement system

This system has two plastic 3D printed parts, two parts made with a sheet of methacrylate and two made of steel sheet.

The basis of this system and the pointer are made of steel 1 mm thick as in the pictures below.

Picture 37 Basis for the measurement system

Picture 38 Pointer

Those two parts were cut with a bench shear and the first one was bent to reach those shapes. The second one was drilled and filed to reach that shape.

The two parts 3D printed with ABS are made to hold the pointer which has to be stuck in the highest place the pendulum has reached.

Picture 39 Pointer restraint (down)

Picture 40 Pointer restraint (up)

The two parts made of methacrylate are just to prevent the user touching the measurement system while making a test. It would be a waste of time if a specimen is broken and the data is invalid because it is needed another specimen.

Picture 41 Lower glass of the measurement system

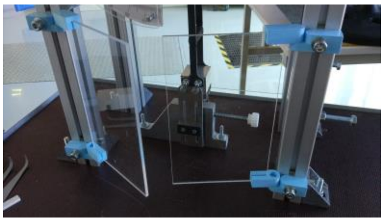
Picture 42 Upper glass

The first part is between the scale and the pointer and the second one is over the pointer. For this, it has been used a vertical cutting machine for plastic. After that, some holes have been made in the three parts with this shape in order to have all the holes in the same place. And these are all the parts in the measurement system.

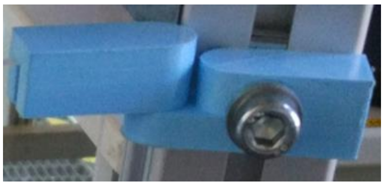
3.3.6 Other parts

In this last chapter it is possible to see some other parts that were made or ordered out of the other systems.

The first two parts are two security pieces. The first one is made of ABS with a 3D printer used to hold the hammer when the specimen has to be changed. The second is a plastic cover to prevent the user from introducing the hands while the machine is working.



Picture 43 Security systems



Picture 44 Support of security system

The second part is made with methacrylate sheet cut and drilled and the first one is just 3D printed in ABS.

Some other parts that are shown here are the bearings. They were ordered in the company ETRA and it included the following parts: two self-aligning bearings, two adapter sleeve, two housings, two locating rings, two seals and one end cover.

Picture 45 Bearings

Those are de bearings used for this project and they are precise enough for this measurement machine.

3.4 Assembly

For the assembly almost all the parts have been attached using bolts, screws and nuts. However, few of them were welded in order to avoid unnecessary weight and making holes in demanding parts.

In this chapter it is explained how the system was assembled and how should be assembled in order not to have any problems.

3.4.1 Hammer

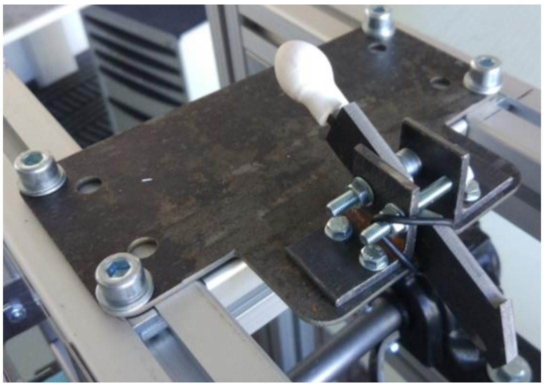
The hammer has some parts affixed using bolts and nuts. The arm is attached to the axis using M5 bolts and nuts in the other side through the clearance holes. Both arm bent sheets are connected with the squared profile welded to them. At the bottom of it there is screwed the assemble part using long M6 screws and nuts to affix both sides of the arm at the same time. Also, there are the two rails for counterweights screwed in the same way. Finally the striking part is united using four M8 screws introduced in the threaded holes of the assemble part.

Picture 46 Hammer

In the picture above it is possible to see how everything is assembled.

3.4.2 Hammer releasing system

First of all the both supports of the holding lever were screwed to the basis with M4 screws and nuts. Between these two supports there are the lever and the torsion spring pierced with a M5 screw which is used as an axis for the lever. There is also another screw functioning as an end for the lever. The handle is just glued to the lever and the basis is screwed to the frame using the T-nuts.

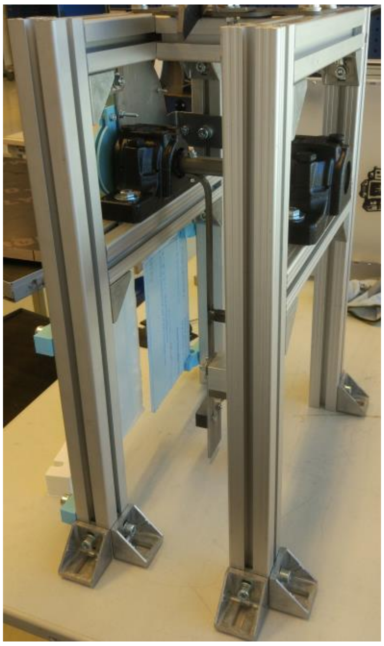


Picture 47 Releasing system

In this picture is possible to see how everything is assembled.

3.4.3 Structure

The structure is simply affixed using the T-nuts, the angles and the M8 bolts. In the picture below is possible to see how it has to be mounted.

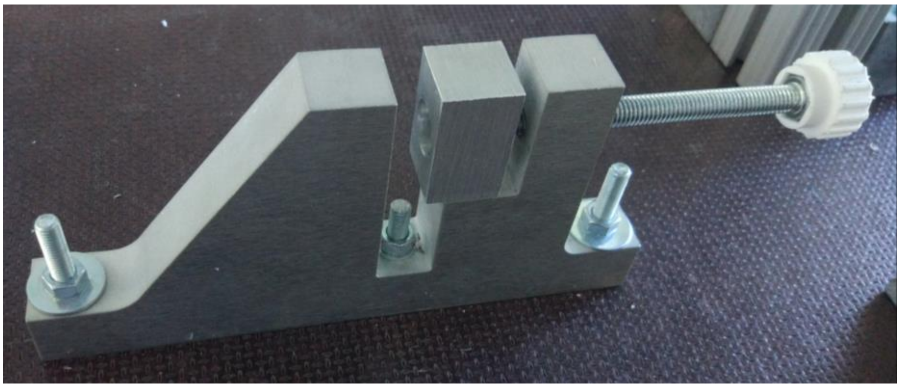


Picture 48 Structure

This is the whole structure of the system. Afterwards, the foundation is attached using long screws.

3.4.4 Support/Clamping block

This is just screwed to the basis using the M6 bolts. The threaded axis is screwed on the support block and introduced in the hole of the clamping block which is pulling this part. Finally the lever to rotate the axis is piercing the axis. There is also another metal sheet to avoid unnecessary movements of the axis to tighten the specimen.

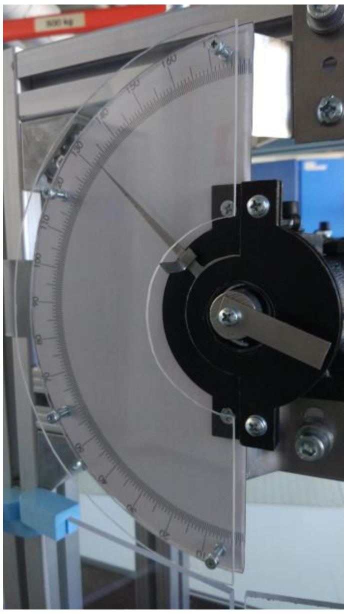


Picture 49 Support/Clamping block

In this picture is possible to see how everything is assembled.

3.4.5 Measurement system

The 3D printed parts can be assembled together using the M4 bolts on both sides introducing the pointer between them. Those two screws are also used to calibrate the friction of the pointer to have enough friction to stop the pointer but not too much to avoid energy losses. This assembly is attached to the basis of steel using two M4 bolts, but before it has to be affixed the first methacrylate sheet which will attach the scale between this and the basis. Finally we used four M3 screws to maintain the second methacrylate layer separated from the pointer and also for fastening the lower glass to the basis (the first glass only had the two screws of the 3D printed parts).



Picture 50 Measurement system

The assembly of this subsystem can be seen in the picture above.

3.5 Testing

For the testing, it has been followed the same standards used for the designing, the ISO 13802. In this document is explained which parts need to be test and what to do in order to test the Izod machine. Below there are all the requirements that need to be tested before proceeding with the normal use of any impact test machine. The following list is pointing all the requirements the manufacturer should certificate and it has to be done just once.

- Centre of percussion – The centre of percussion shall be ±2.5 mm at the centre of strike. To verify this the pendulum has to be released from a height that results in a swing of a maximum of 5º, on average. The period of oscillation has to be determined as the mean value of four determinations. So, using the following formula is possible to determine the centre of percussion.

  $$l_{CP} = \frac{gT^2}{4\pi^2}$$

  Where T is the oscillation period.
- Axis of rotation – The axis of rotation should be parallel within ±2/1000 relative to the reference plane.
- Pendulum plane of swing – The plane of swinging shall be in 90º±0.1º relative to the axis of rotation.
- Mass of frame – The mass of the frame shall be at least 40 times the weight of the pendulum.

In the next list there are all the requirements that have to be calibrated in of any impact test machine.

- Installation – The adjustment screws shall be fixed after levelling in order to maintain the frame in position and the stiffness of the mounting. During an impact test, there shall be no displacement of the frame or the foundation.
- Levelness – The machine shall be installed so that the reference plane is horizontal to within 2/1000.
- Axial play of the pendulum bearings – The endplay in the bearings of the pendulum spindle in the axial direction shall not exceed 0.25 mm.

- Radial play of the pendulum bearings – The radial play shall not exceed 0.05 mm when a torque of 2±0.2 N is applied.
- Mechanism for holding and releasing the pendulum – This shall release the pendulum without initial impulse, retardation, or side vibration or any other interference that would result in energy loss.
- Free hanging position – When hanging free, the striking edge shall be within 6.35 mm of the position where it would just touch the reference specimen.
- Contact between specimen and striking edge – The striking edge should make full contact on the specimen. To check this, the specimen should be covered by thin tape and the striking edge by carbon paper. Afterwards, the pendulum is released and the full paper should be painted by the carbon.
- Impact length – The impact length shall be within 1% of the centre of percussion is the length from the axis of rotation to the striking edge.
- Speed of the pendulum at instant of impact – The impact velocity shall be 3.5±0.35 m/s. The formula to calculate it is:

$$v_{SE} = \sqrt{2gl_{CP} \cdot (\cos\theta_R - \cos\theta_0)}$$

For Izod test machines there are the next requirements that need to be checked before continuing.

- Radius of striking edge – The striking edge shall have a cylindrical surface (with a radius of 0.8±0.2 mm) with its axis horizontal and perpendicular to the plane of motion of the pendulum.
- Parallelism of striking edge and the face of the specimen
- Parallelism of clamp faces in horizontal and vertical direction – The specimen clamped in place, the clamp faces shall be parallel in both the horizontal and vertical direction.
- Horizontality of the top surface of the clamp – The top surface of the clamp shall be horizontal relative to the reference plane.
- Perpendicularity of the clamp faces and the top surface of the clamp – The angle between the clamp faces and the top surface of it shall be 90±0.1º.
- Radius of support block – The top edge of the support, about which bending takes place, shall have a radius of 0.2±0.1 mm.
- Height of striking edge above top surface of support – The striking edge shall be 22±0.2 mm above the top surface of the clamp.

It is also important to verify the losses due to friction. Here it is explained how to calculate and test the friction losses. In this case we are going to determinate the following energy losses.

- Friction in the pointer – To evaluate this loss the machine should operate without a test specimen to obtain the first reading. This first reading will be named $W_{f,1}$. After, without resetting the pointer, release the pendulum again obtaining a $W_{f,2}$. This procedure shall be done thrice and the loss due to friction in the pointer shall be the subtraction of the mean of the first measurements from the mean of the second measurements.

$$W_{f,P} = \overline{W_{f,1}} - \overline{W_{f,2}}$$

  Where $W_{f,P}$ is the approximation of the energy loss due to the friction of the pointer.

- Losses due to air resistance and bearing friction – To determine this first it is important to calculate the theoretical potential energy of the hammer. To do this, first of all, is letting the pendulum make one swing. Afterwards, the procedure for the pointer loss has to be repeated but this time, the pendulum will continue swinging free. At the beginning of the tenth forward swing, the pointer shall be repositioned and this measurement shall be recorded as $W_{f,3}$. Now using the equation below

$$W_{f,AB} = \frac{W_{f,3} - W_{f,2}}{20}$$

  The $W_{f,AB}$ is the energy lost due to the air resistance and the bearing friction for one swing.

Finally, the total energy lost shall be calculated using the following equation.

$$W_f = \frac{1}{2}\left[W_{f,AB} + \frac{\theta_R}{\theta_0}\left(W_{f,AB} + 2 \cdot W_{f,P}\right)\right]$$

The total losses due to friction for one swing shall not exceed the 1% of the energy delivered by the pendulum.

It is important to verify those calculus if the machine is moved to a new location or is subject to major repairs or adjustments or if there is any reason to doubt the accuracy of the results given. Also, the verifications shall be performed every two years to have it under favourable conditions of service.

4 RESULTS

In this chapter it is going to be explained how the flow of each part in the project was, and the goals reached from the ones aimed when the project started.

4.1 Designing

In the beginning, the design was something simple. There were some problems to start the project because there was no access to the workshop and the laboratories and the standards were not taken into account.

For those reasons, the first designs were really simple and there was a lack of precision. However, after some time it was got the standards that the main user wanted to use and the project changed the course. The designs started to have more precision, the design was trying to achieve some requirements that were needed to fulfil in order to have a standard machine.

In addition, some days later, the permission for the workshop and the laboratories were given and that gave the chance to make more realistic designs. The available material was already known and it was possible to design the parts already thinking how to produce them.

Even though all the material was already available, there were some points that were overlooked. The requirements were practically determining how the hammer should be, where the mass centre should be, the length of the hammer for a given energy, and other physical properties. Thanks to that it was possible to make a final design.

Nevertheless, the world is not ideal and some changes were made while the manufacturing and ordering were running. Sometimes because some pieces were too expensive to make, some other times because it was thought to do something in the workshop but it was not possible to do it there. And some changes were made because it was not enough time to order some parts.

4.2 Manufacturing and ordering

Even though most of the people thinks the designing is the most creative part, for this project, the manufacturing was an inventive process. While a design is made, there is almost no problems. However, when that perfect design has to be made, everything is imperfect and it is important to think the best way to solve the problem.

When the manufacturing started there were left almost all the parts ordered. For that reason the first to do were the systems that could be entirely done in the university, like the measurement system. Although there were not a laser cut machine, it was managed to manufacture some metal sheet parts. Some other parts were 3D printed and everything was handmade.

After some time, aluminium parts and the laser cut parts arrived. With that was possible to make the rest of the subsystems. The most difficult part was the assembly piece of the hammer and it had to be repeated three times. First of all because the aluminium taken was too soft. Afterwards, because the holes were wrong done. And finally, it was reached a good part which was pretty precise and almost without mistakes.

Another issue found while building was that the laser parts were not bent. So it had to be made manually and there was not a bending machine. The precision for that was not good and for that reason was really difficult to make the bent parts.

The total budget spent in the machine has been 750 € which is under the thousand which was one of the requirements of the TAMK.

4.3 Assembly

The assembly is the easiest part of a project because attaching g some parts together is not difficult. However, in this procedure is where most of the issues are found. The only and most effective way to check a part to see if it is well done is trying to assembly it. For example, if the holes are not correctly done, when trying to assemble those two parts, it is going to be impossible to put the screws piercing both holes.

In the assembly there were some issues found. Most of them were due to the holes. Some holes were in a wrong position and some other were too small to be able to fit some parts inside. Other issues found were the roughness of some surfaces like the pointer surface. In this machine, where it is important avoid losses of energy, the roughness of that parts should be minimum and some parts had to be filed.

The frame was perfectly assembled with the angles and the T-nuts and there was not any problem. Also the releasing system was pretty easy to assemble because almost all the parts were precisely made with the laser cut. The worst problems were with the hammer and also some with the measurement system.

4.4 Testing

In this chapter there will not be explained what was done because it is in the one above. Every checking was done and here the results are going to be explained. Some of them where successful, so they are just going to be listed. The others which did not succeed are going to be explained in detail.

Next, there are all the test made which were inside the admissible values.

- Installation
- Axis of rotation
- Pendulum plane of swing
- Levelness
- Axial play of the pendulum bearings
- Radial play of the pendulum bearings
- Mechanism for holding and releasing the pendulum
- Free hanging position
- Contact between specimen and striking edge
- Radius of striking edge
- Parallelism of striking edge and the face of the specimen
- Parallelism of clamp faces in horizontal and vertical direction
- Horizontality of the top surface of the clamp
- Perpendicularity of the clamp faces and the top surface of the clamp

- Radius of support block
- Height of striking edge above top surface of support

After that, they were made some checking and calibration.

- Centre of percussion – For the centre of percussion it was followed the procedure and the times obtained were pointing that the centre of percussion was so high. For that reason was repeated changing the counterweights position and finally the times resulting were: 10.5, 10.4, 10.4, 10.5 seconds.
  Using the equation given above, it is possible to determine the centre of percussion as

$$l_{CP} = \frac{g \cdot 10.45^2}{4\pi^2} = 0.27136\, m = 271.36\, mm$$

- Mass of frame – This was not calculated because there was left to think the foundation where the frame is going to be affixed.

  Impact length – The impact length of the hammer was accurately measured and the real value of the length of the pendulum was, actually 271.02 mm. This shall be compared with the centre of percussion position.

- Speed of the pendulum at instant of impact – This speed was also calculated using the formula above and the result is the next

$$v_{SE} = \sqrt{2g \cdot 0.27136 \cdot \cos(150)} = 3.152\, m/s$$

  The nominal value should be 3.5m/s. However it is still within the error admissible.

- Friction in the pointer – For the energy losses of the friction pointer, some angles were got. However, that angle shall be translated in an energy delivered.
  The way to proceed is using the equation to calculate the potential energy.

$$W = L \cdot F \cdot (1 + \cos(180 - \theta_R))$$

  Although the potential energy, can change it is possible to use this value to calculate the energy losses because the error is imperceptible.
  The product of L·F it is going to be explained in the procedure, but in this measurement it is going to be used the value of 1.8 N·m.

The angles measured for the $W_{f,1}$ were: 143.5, 143.5, 143.5 degrees. The angles measured for the $W_{f,2}$ were: 145.0, 144.5, 145.0 degrees. The calculation of both energies is

$$W_{f,1} = 1.8 \cdot (1 + \cos(180 - 143.5)) = 3.247\, J$$

$$W_{f,2} = 1.8 \cdot (1 + \cos(180 - 145)) = 3.271\, J$$

The values of the $W_{f,1}$ are: 3.247, 3.247, 3.247 joules. And the average is 3.247 J. For the $W_{f,2}$ there are the next: 3.274, 3.265, 3.274 joules. And the average is 3.271 J.

Then, the friction of the pointer is

$$W_{f,P} = 3.247 - 3.271 = -0.025\, J$$

- Losses due to air resistance and bearing friction – for those losses it is used the same procedure. But the angles obtained were the following: 111.0, 110.5, 111.0 degrees.

$$W_{f,3} = 1.8 \cdot (1 + \cos(180 - 111)) = 2.445\, J$$

The next values are: 2.445, 2.430, 2.445 joules. And the average is 2.440 J.

Now, applying the formula given in the testing chapter,

$$W_{f,AB} = \frac{2.440 - 3.271}{20} = -0.042\, J$$

Those are the losses due to the air resistance and the bearing friction for one swing.

Finally, the total energy lost is

$$W_f = \frac{1}{2}\left[-0.042 + \frac{145}{150}\left(-0.042 + 2 \cdot (-0.025)\right)\right] = -0.044\, J$$

This value should be diminished from the value given in the test.

As a final test it was made the procedure explained in the appendix 2 to check the resistance of 3D printed PLA with an infill of 20%.

The angles results obtained from it were: 139.5, 139.0, 139.5, 140.0, 138.5, 138.5, 138.0, 139.0, 137.5, 138.0 degrees.

Using this, the energy spent was the diminish of the energy of 138.8º from the energy of the hammer (in this case, 3.36 J). It is important to take into account the energy losses calculated above. Here there is the example of the first angle, but it has to be done 10 times.

$$W_{PLA} = 3.36 - 0.044 - 1.8 \cdot (1 + \cos(180 - 139.5)) = 0.147\, J$$

The rest of the values are: 0.147, 0.158, 0.147, 0.137, 0.168, 0.168, 0.179, 0.158, 0.189, 0.179 joules. So the average is 0.163 J

The way to express the impact resistance is in J/m^2 for that reason it has to be divided by the section, which is 4x8 mm.

$$W_{PLA} = \frac{0.163}{0.004 * 0.008} = 5094.5 \frac{J}{m^2}$$

To express it as made in ASTM 256-06, it would be

$$W_{PLA} = \frac{0.141}{0.008} = 20.38\, J/m$$

5 CONCLUSIONS

The main aim of this project, beyond of the design, the assembly and the test, was making an Izod test machine. A test machine able to test some 3D printed plastics whose impact strength is needed. It was also important that this machine was able to fulfil all the requirements from the standards as much as the customer.

The main objective has been reached, that is, the Izod test is working and able to test all the plastics that are currently used in 3D printers at TAMK. The most important requirements, like the requirements of the hammer, have been fulfilled. The customer requirements like the possibility to calibrate the machine are accomplished as well. And the machine is completely safe.

The total budget spent in the machine has been 750 €, which is greatly under the estimated expenses for this project.

After building the machine it was tested and it pass almost all the test in the first instance. After some mends, the machine succeeded in the rest of the test and is ready to test any of the 3D printed plastics proposed.

The total energy delivered by the hammer is 3.36 J but it is important to diminish the energy losses, whose value is about 0.065 J. This value is out of the 1% of the energy delivered, for that reason, those losses should be reduced to the minimum. However, the bearings still needed a correct lubricating, which was not done due to the lack of time. It is probably that, just with the proper maintenance the losses decrease enough to fulfil this requirement.

However, the machine was finally built and it is able to calculate the resistance of some 3D printed plastics.

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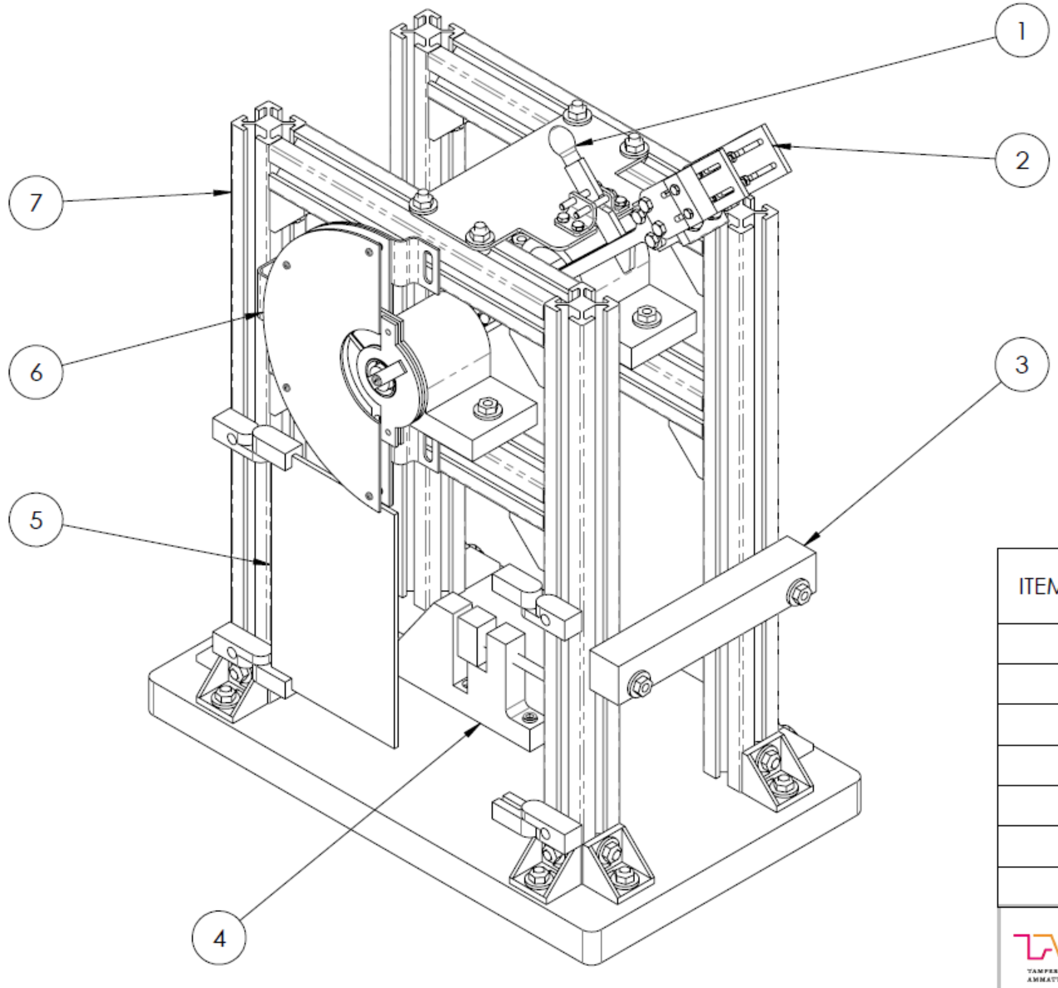
APPENDICES

Appendix 1. Drawings



ITEM NO.	PART NUMBER	Predeterminado/QTY.
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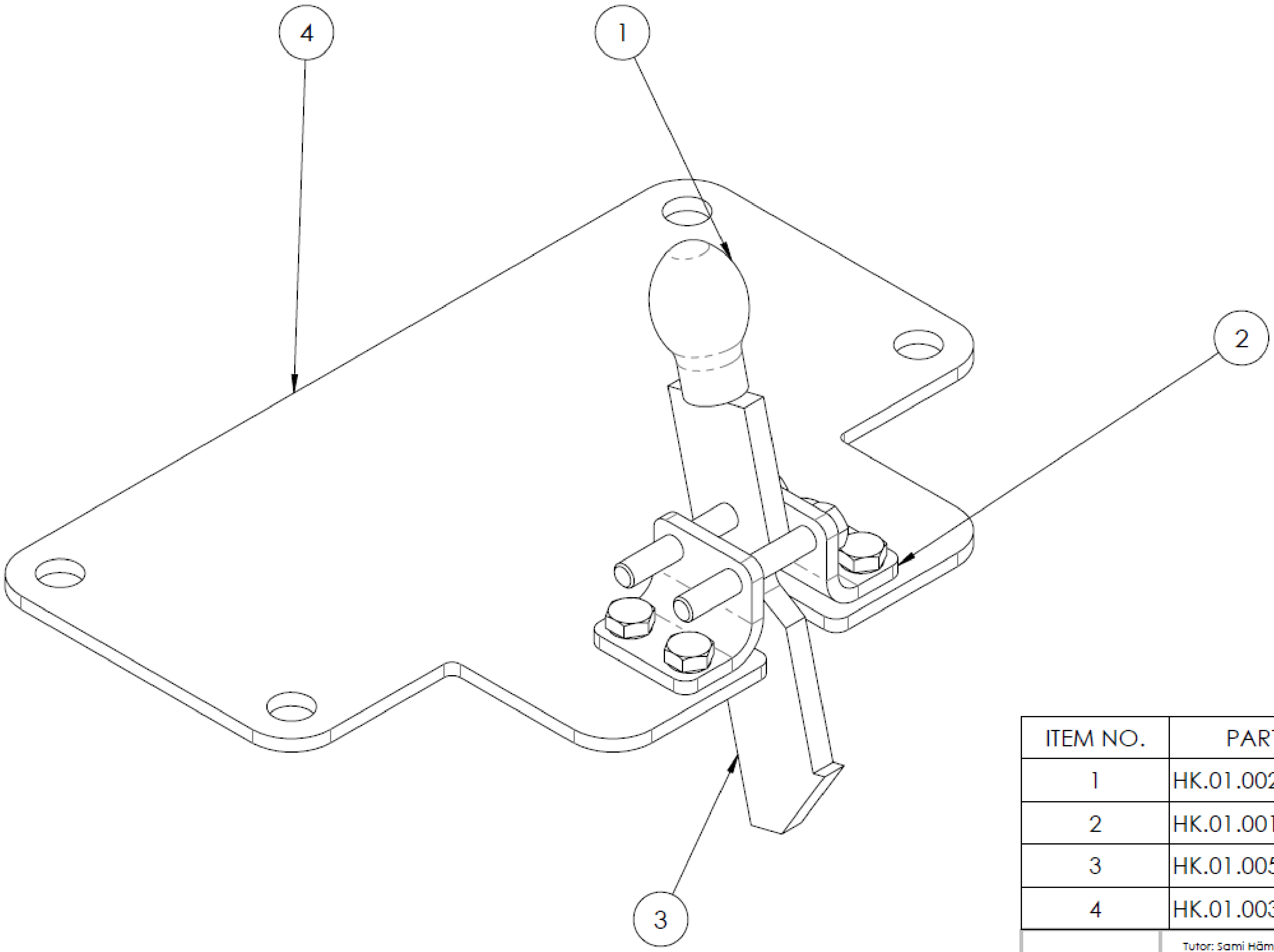
2	HA.02.001.06	1
3	SE.01.001.01	1
4	SU.02.001.02	1
5	SE.02.001.01	2
6	MS.02.001.01	1
7	ST.02.001.02	1

TAMK TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: -	Weight: 41849 g
	Author: Jordi Marsà	26/04/2018	Scale: 1:4
	Izod Test Machine		No.: -



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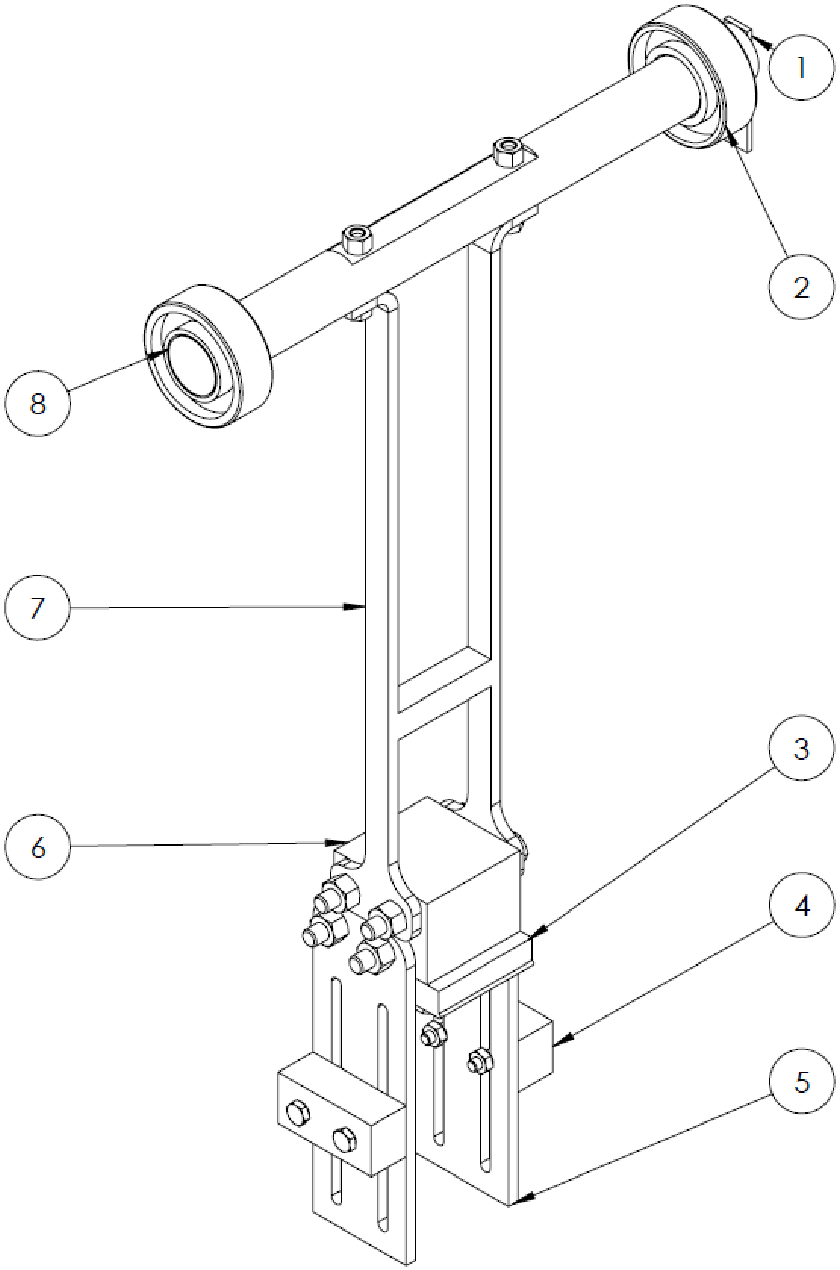
2	HK.01.001.03	2
3	HK.01.005.01	1
4	HK.01.003.02	1

TAMK TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: -	Weight: 515 g
	Author: Jordi Marsà	26/04/2018	Scale: 1:1
	HK.02.001.02		No.: 1



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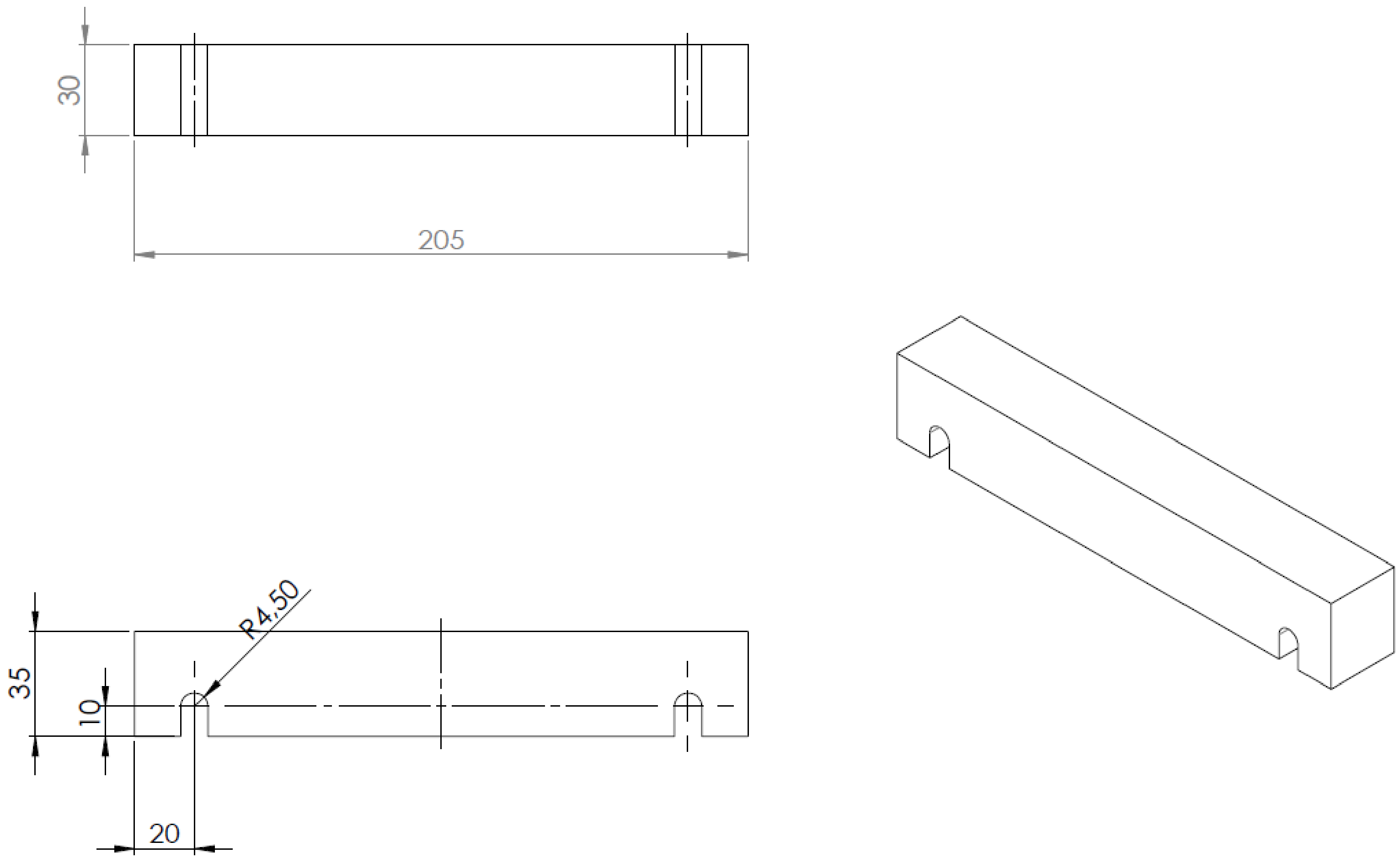
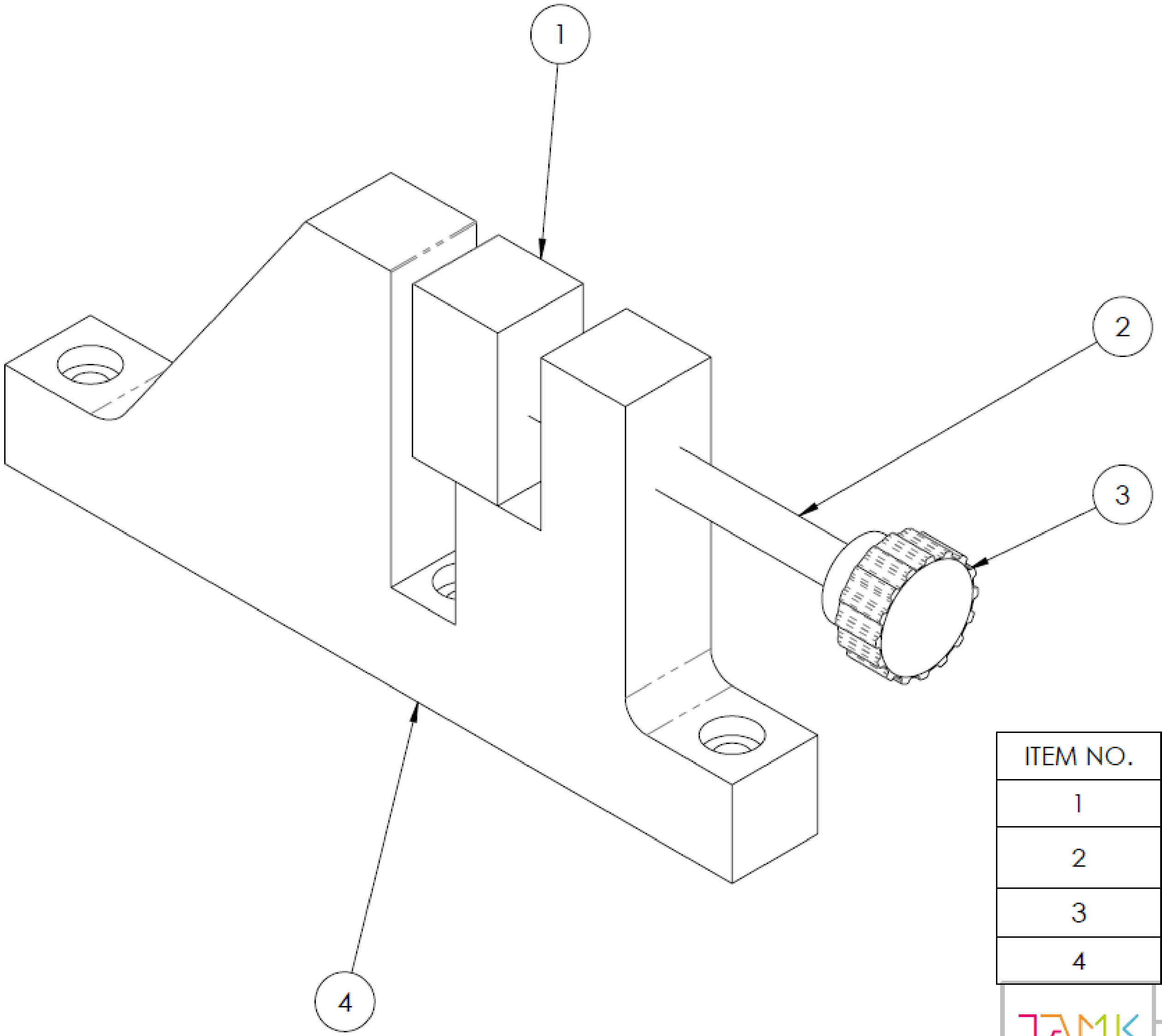
3	HA.01.002.02	1
4	HA.01.004.07	2
5	HA.01.006.05	2
6	HA.01.005.06	1
7	HA.01.003.08	1
8	HA.01.001.04	1

TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: -	Weight: 1287 g
	Author: Jordi Marsà	26/04/2018	Scale: 1:2
	HA.02.001.06		No.: 2



TAMK TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: PLA	Weight: 212 g
	Author: Jordi Marsà	26/04/2018	Scale: 1:2
	SE.01.001.01		No.: 3

8.27 in



ITEM NO.	PART NUMBER	QTY.
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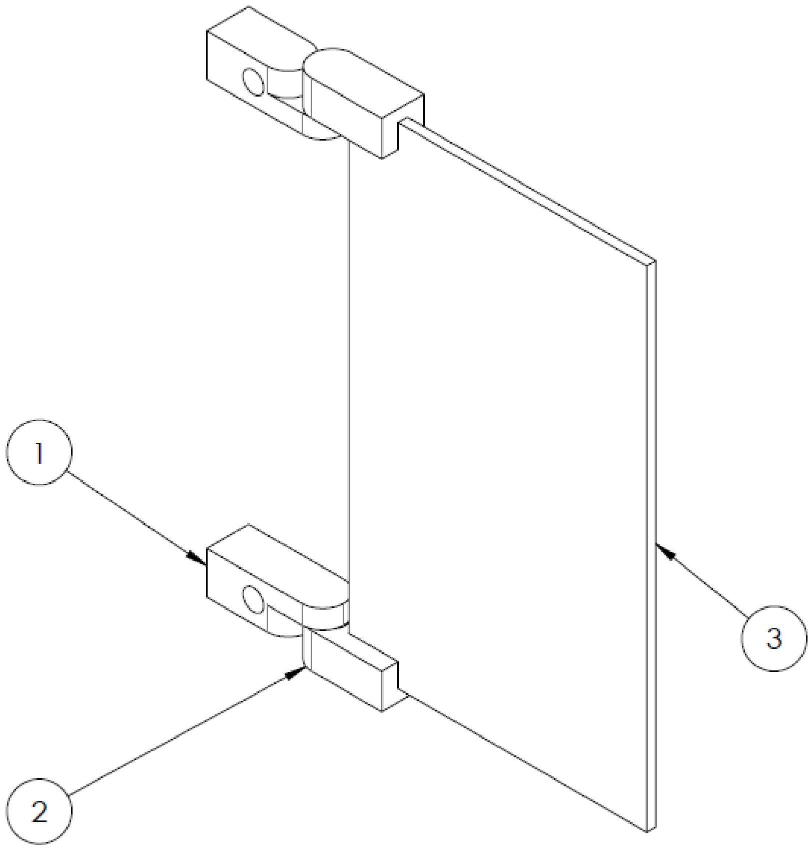
2	ISO 4014 - M8 x 80 x 22-N	1
3	SU.01.003.01	1
4	SU.01.001.02	1

TAMK TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: -	Weight: 462 g
	Author: Jordi Marsà	26/04/2018	Scale: 1:1
	SU.02.001.02		No.: 4



ITEM NO.	PART NUMBER	QTY.
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2	SE.01.003.01	2
3	SE.01.004.01	1

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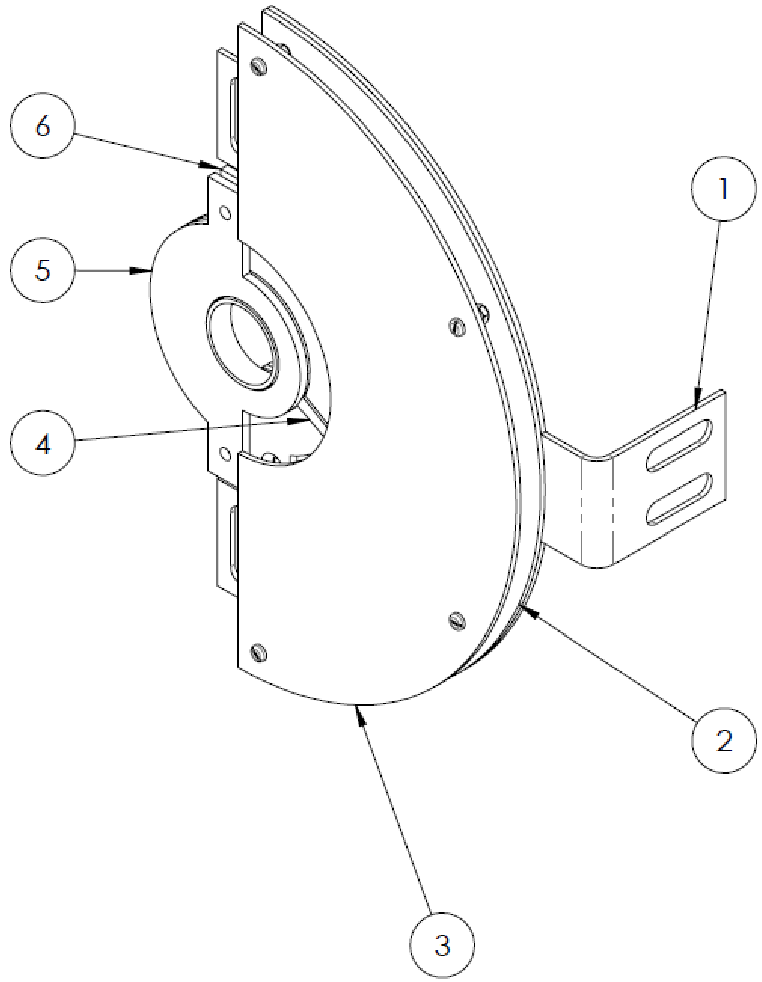
	Author: Jordi Marsà	26/04/2018	Scale: 1:2
	SE.02.001.01		No.: 5



ITEM NO.	PART NUMBER	QTY.
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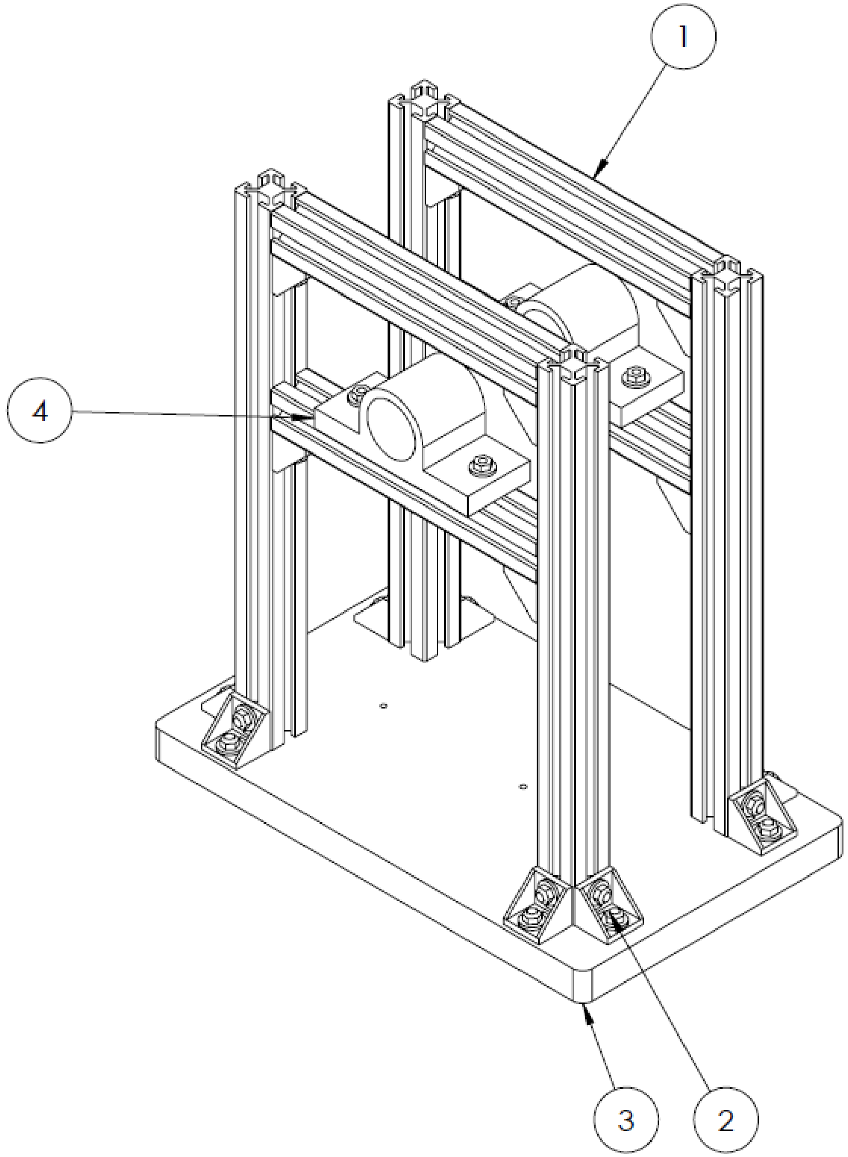
2	MS.01.005.01	1
3	MS.01.006.01	1
4	MS.01.002.01	1
5	MS.01.003.01	1
6	MS.01.004.01	1

TAMK TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: -	Weight: 567 g
	Author: Jordi Marsà	26/04/2018	Scale: 1:2
	MS.02.001.01		No.: 6



ITEM NO.	PART NUMBER	QTY.
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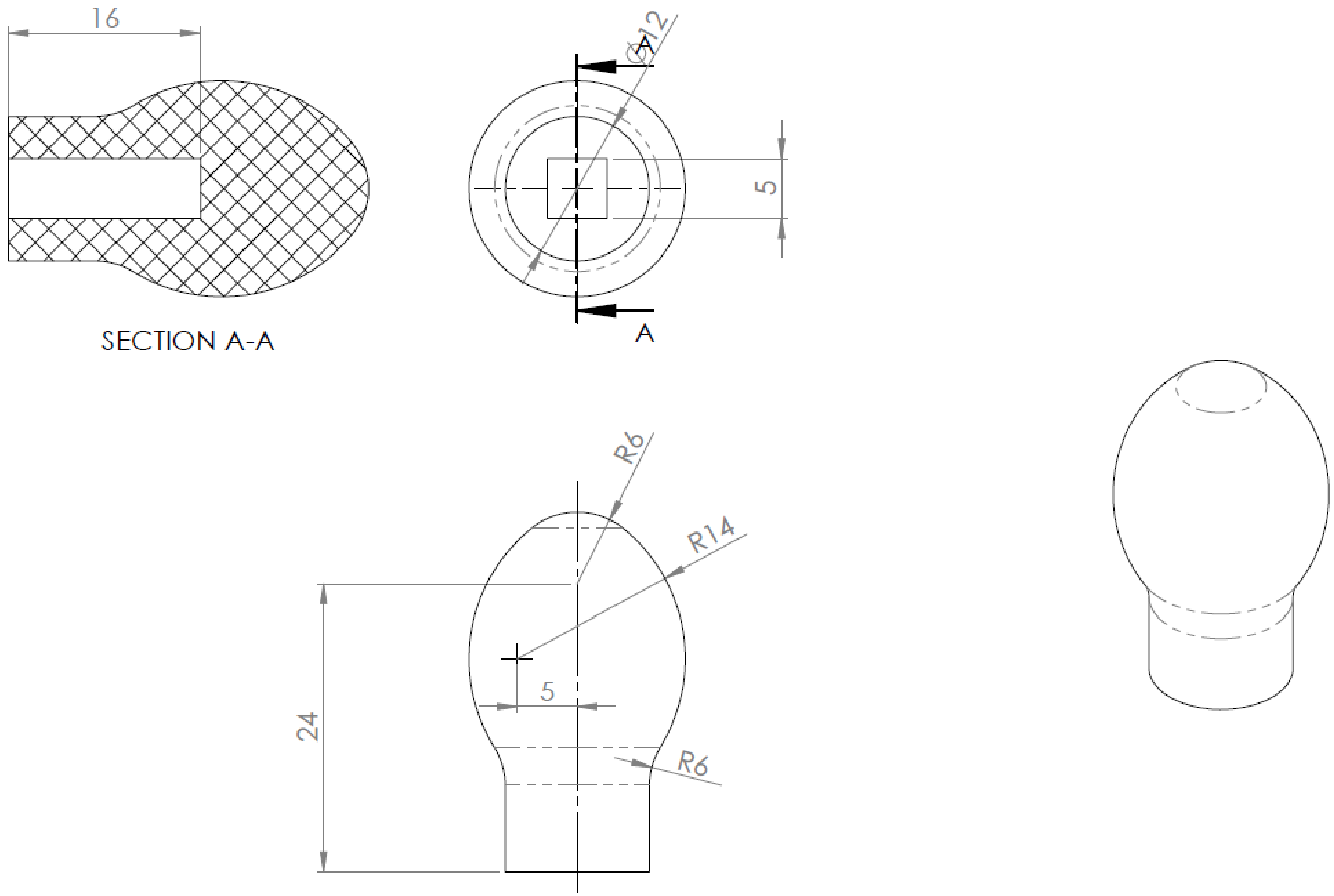
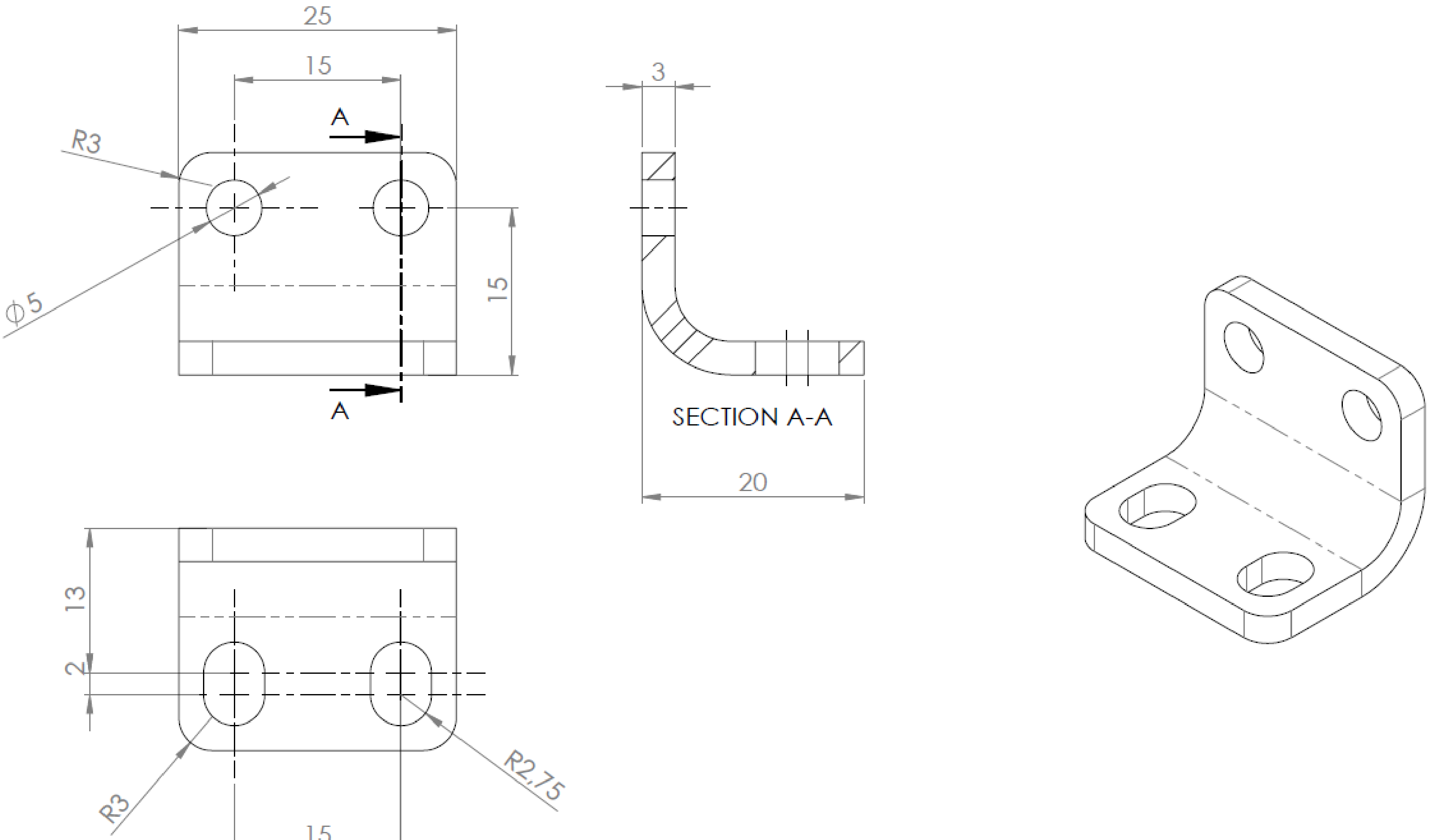
3	ST.01.003.01	1
4	ST.01.004.01	2

TAMK TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: -	Weight: 38470 g
	Author: Jordi Marsà	26/04/2018	Scale: 1:5
	ST.02.001.02		No.: 7



TAMK TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: PLA	Weight: 5 g
	Author: Jordi Marsà	26/04/2018	Scale: 2:1
	HK.01.002.02		No.: 1



TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: Stainless Steel	Weight: 17 g
	Author: Jordi Marsà	26/04/2018	Scale: 2:1
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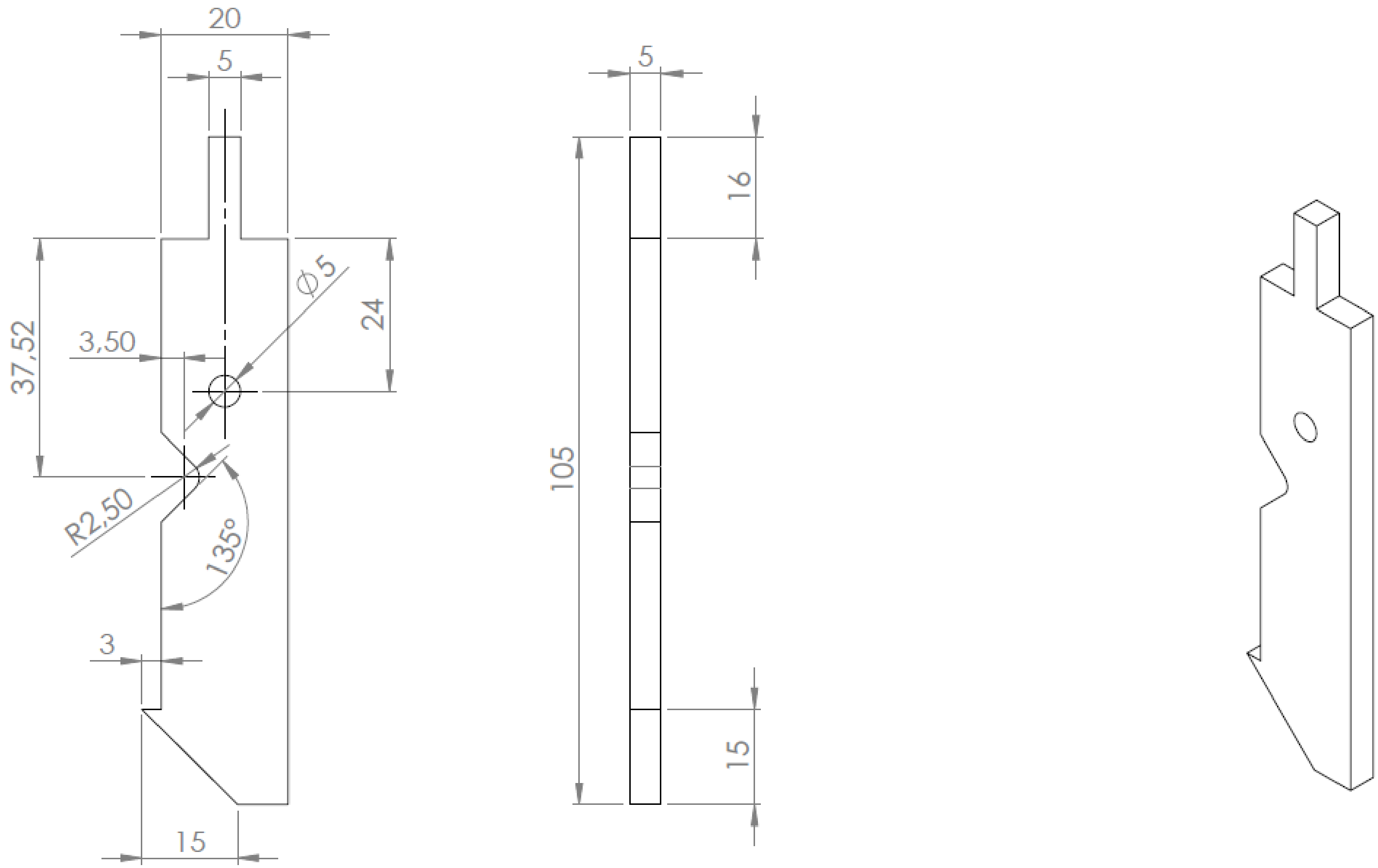
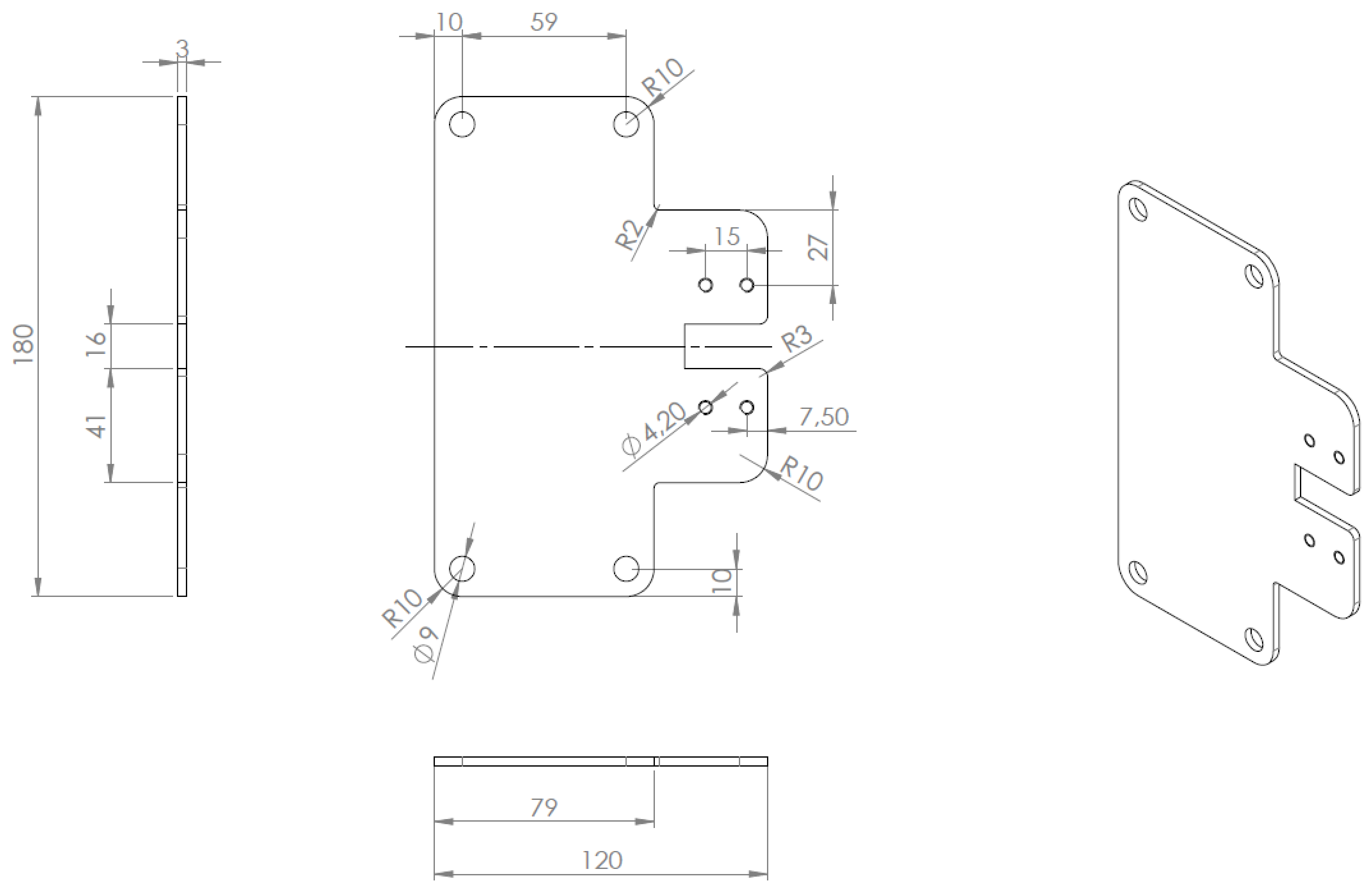
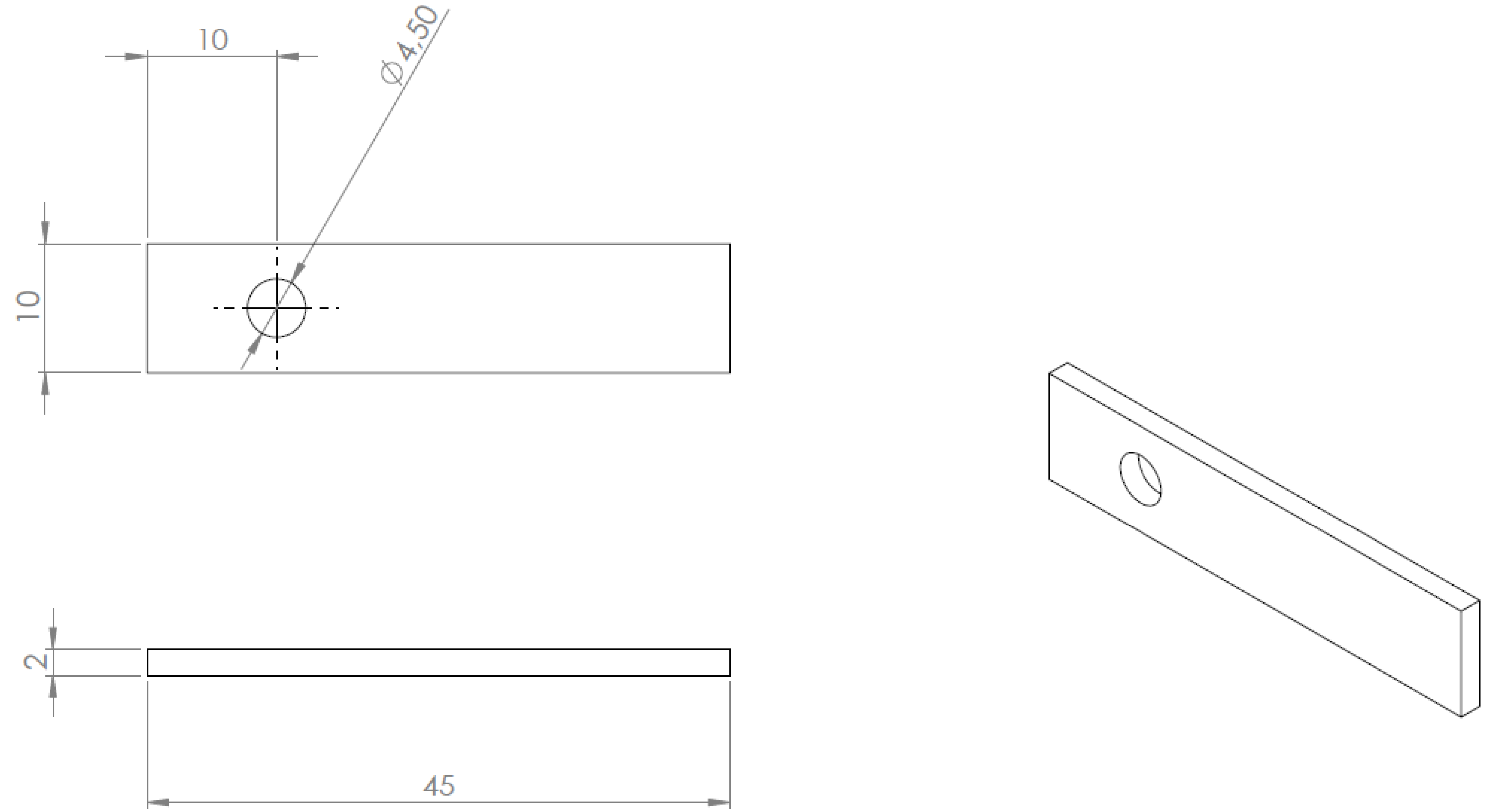


TAMK TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: Steel 5mm	Weight: 67g
	Author: Jordi Marsà	26/04/2018	Scale: 1:1
	HK.01.005.01		No.: 3



TAMK TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: Stainless Steel 3mm	Weight: 405 g
	Author: Jordi Marsà	26/04/2018	Scale: 1:2
	HK.01.003.02		No.: 4



TAMK TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: Stainless Steel	Weight: 1 g
	Author: Jordi Marsà	26/04/2018	Scale: 2:1
	HA.01.007.05		No.: 1

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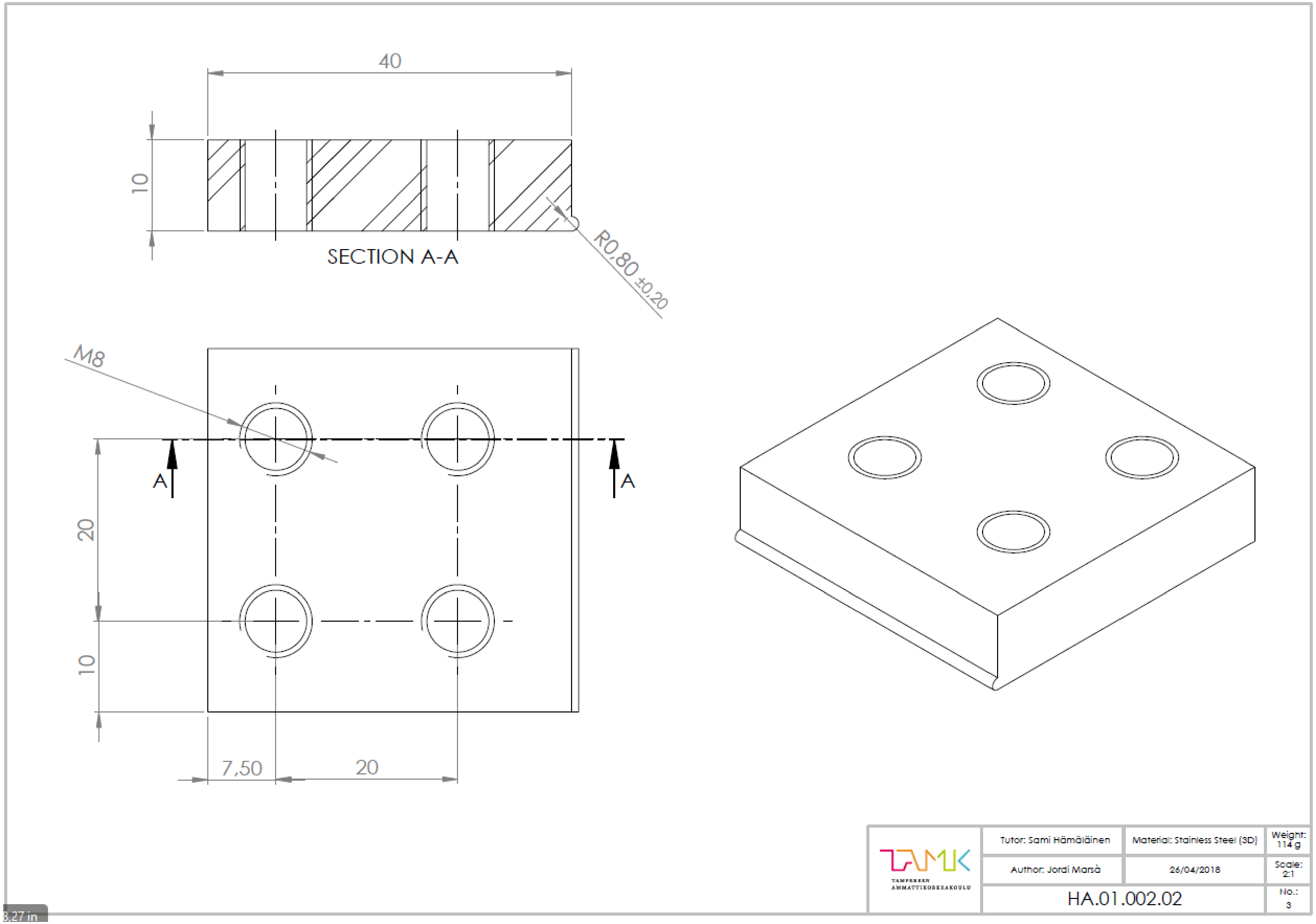
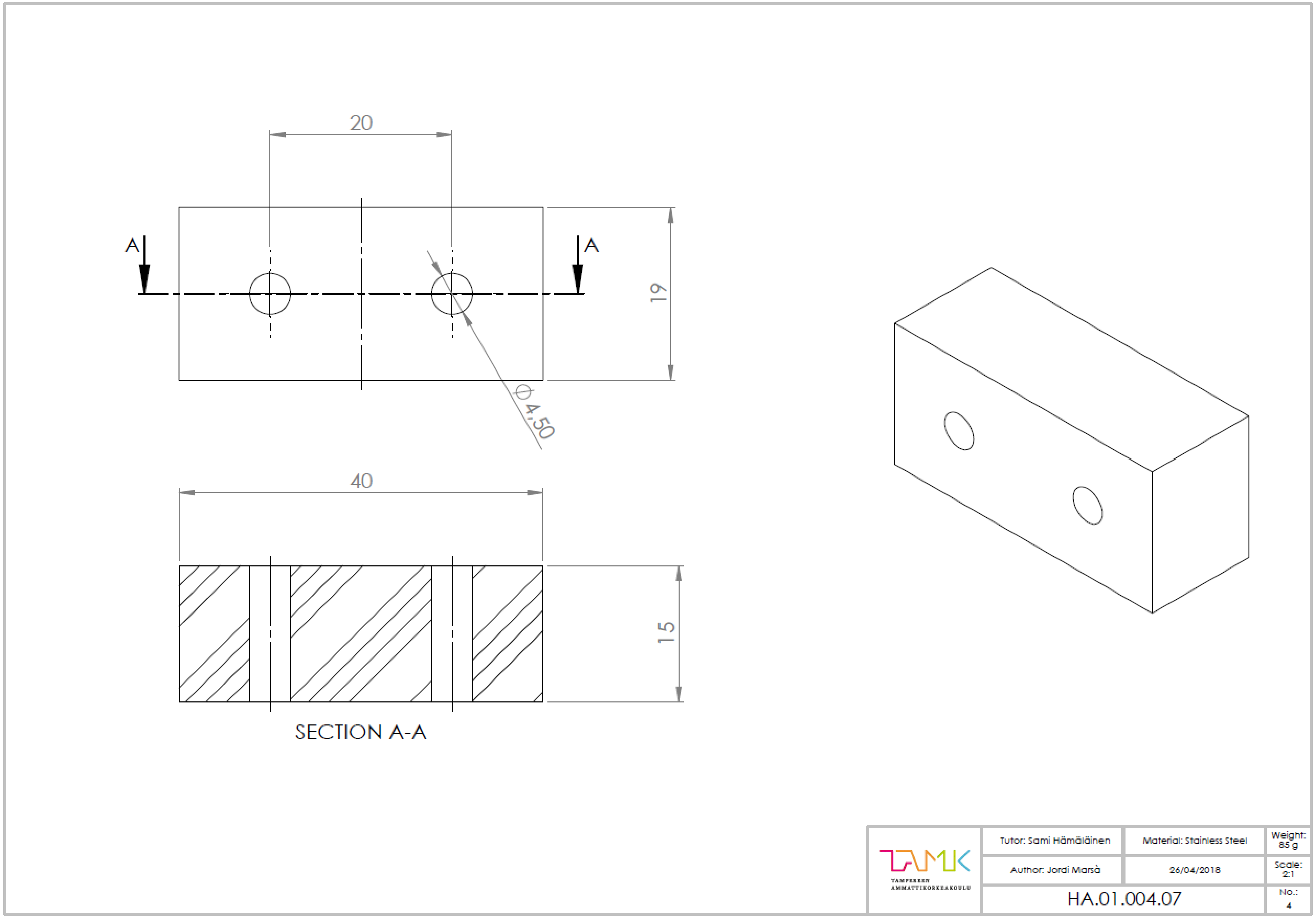
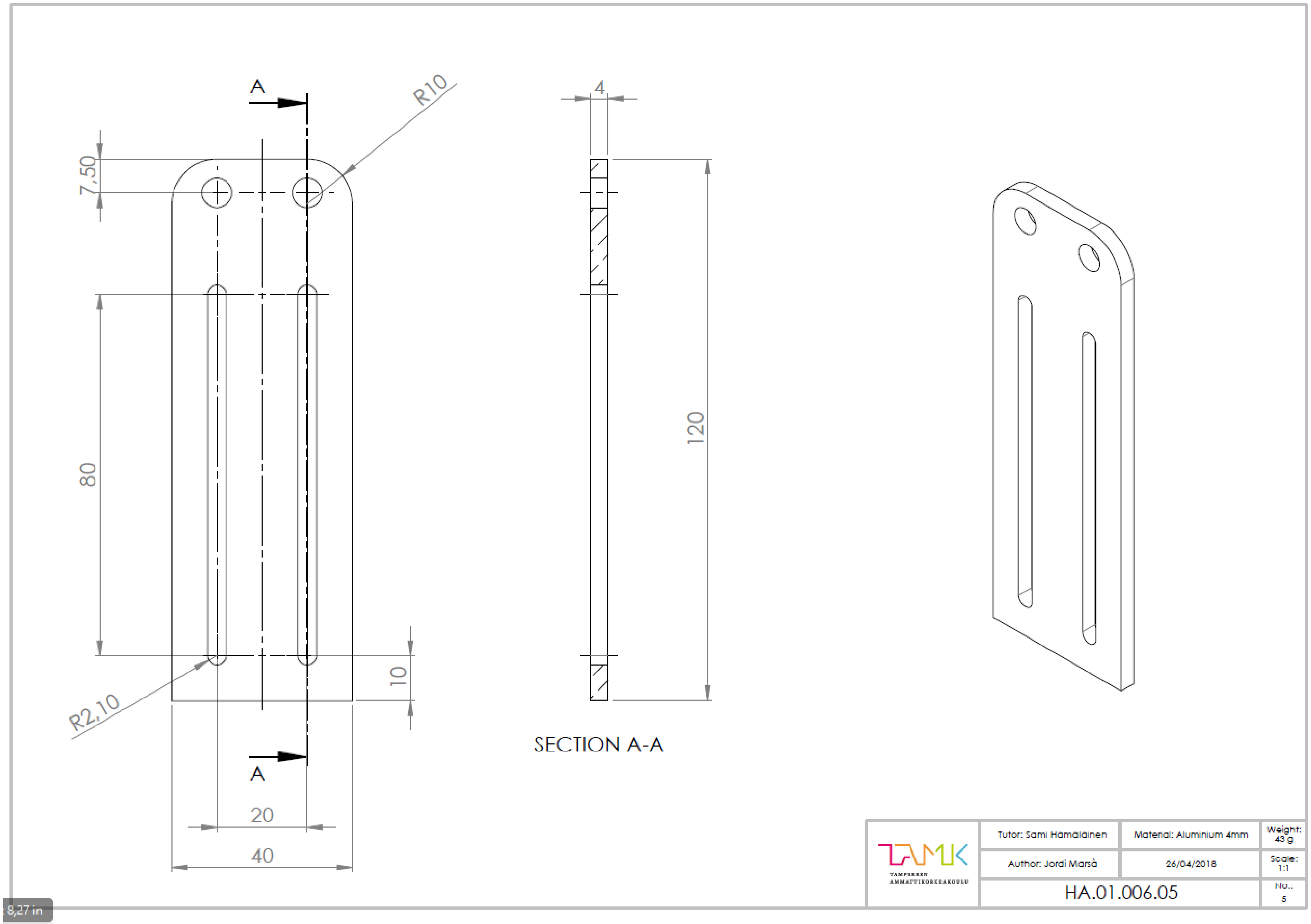

40
10
SECTION A-A
R0,80 ±0,20
M8
A
A
20
10
7,50
20
TAMPEREEN AMMATTIKORKEAKOULU
Tutor: Sami Hämäläinen
Material: Stainless Steel (3D)
Weight: 114 g
Author: Jordi Marsà
26/04/2018
Scale: 2:1
HA.01.002.02
No.: 3
8,27 in


20
A
A
19
Φ 4,50
40
15
SECTION A-A
TAMK
TAMPEREEN AMMATTIKORKEAKOULU
Tutor: Sami Hämäläinen
Material: Stainless Steel
Weight: 85 g
Author: Jordi Marsà
26/04/2018
Scale: 2:1
HA.01.004.07
No.: 4



TAMK TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: Aluminium 4mm	Weight: 43 g
	Author: Jordi Marsà	26/04/2018	Scale: 1:1
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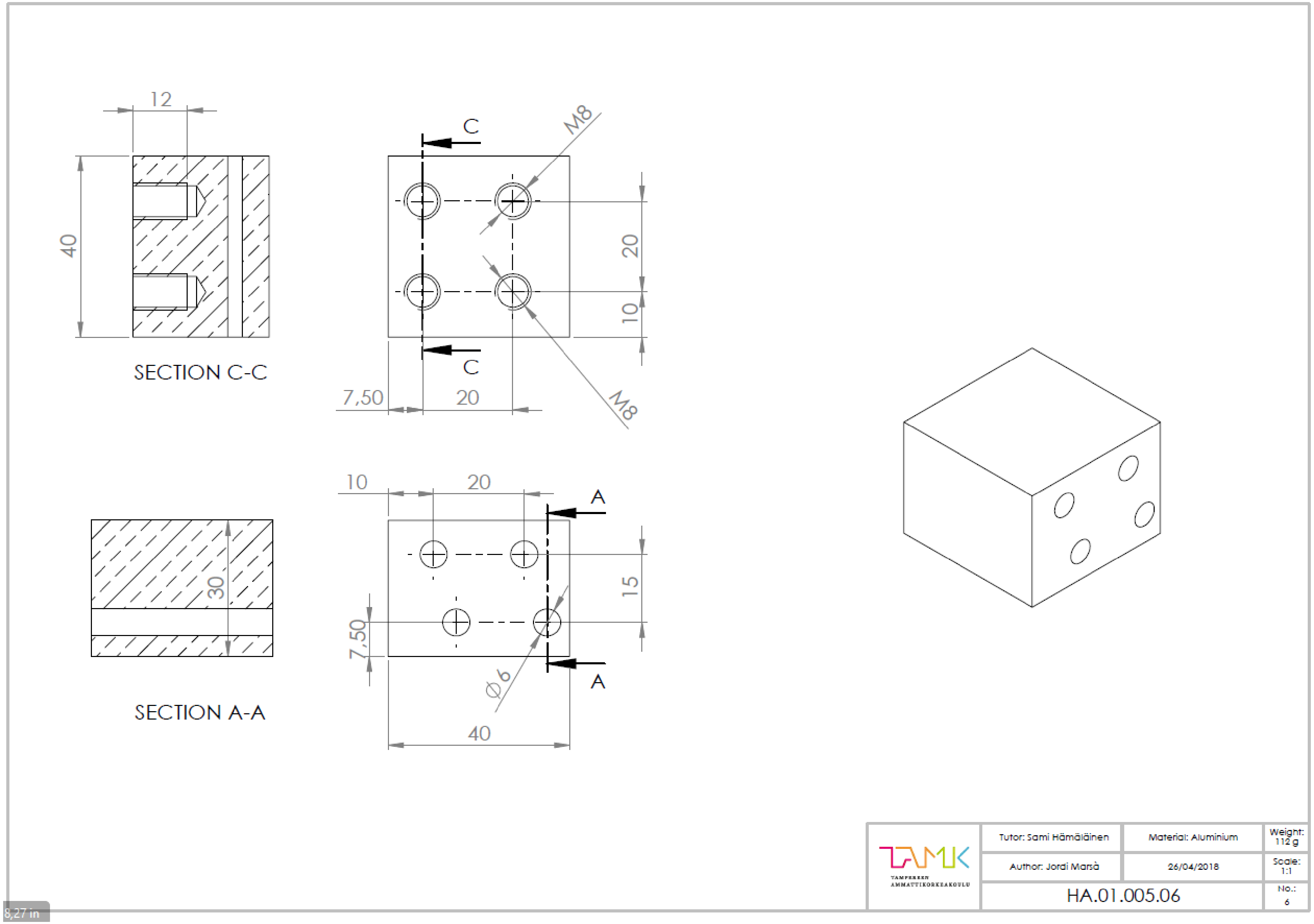
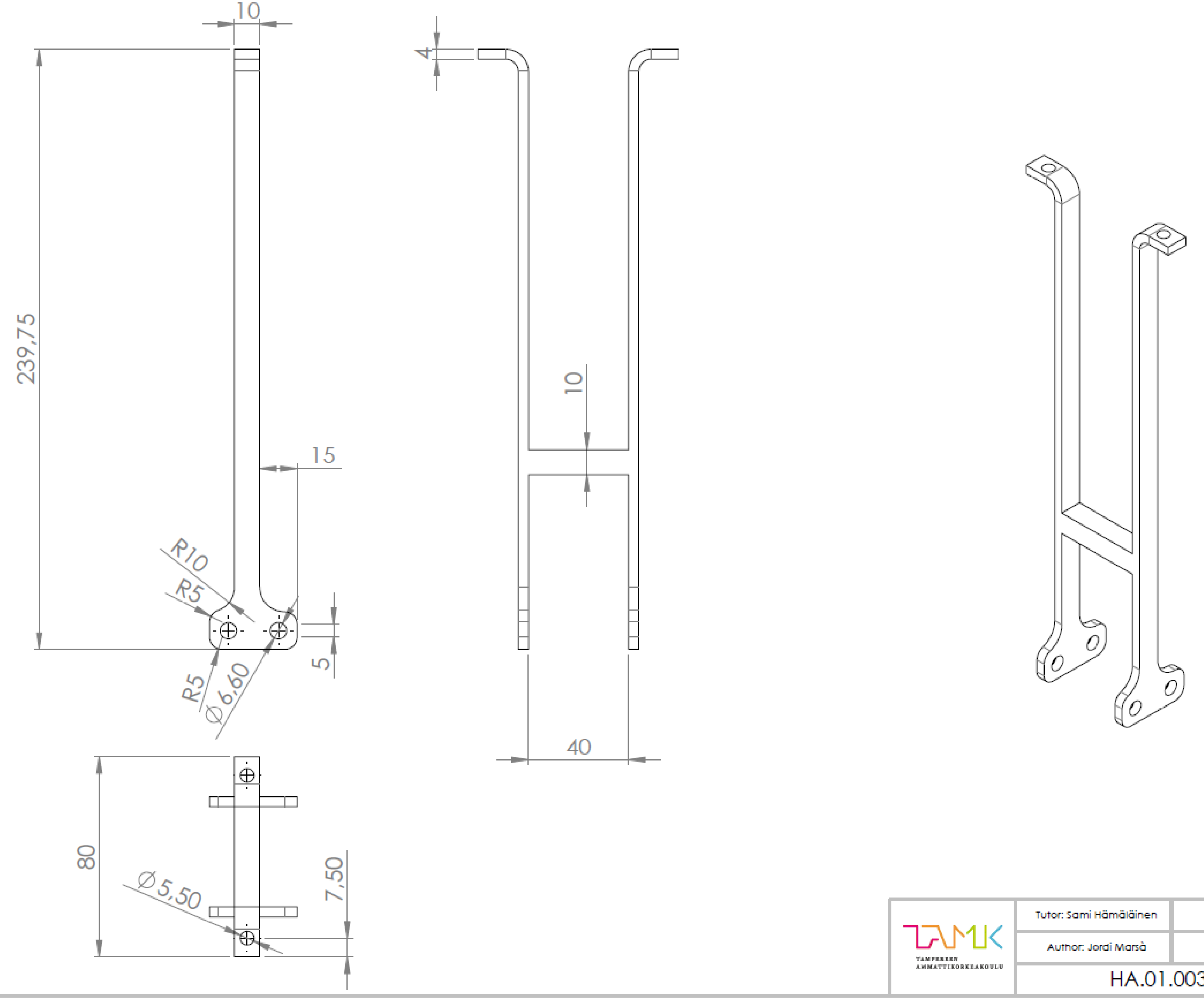

12
40
SECTION C-C
C
M8
20
10
7,50
20
M8
C
SECTION A-A
30
10
20
A
15
7,50
⌀6
A
40
TAMPEREEN AMMATTIKORKEAKOULU
Tutor: Sami Hämäläinen
Material: Aluminium
Weight: 112 g
Author: Jordi Marsà
26/04/2018
Scale: 1:1
HA.01.005.06
No.: 6



TAMK TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: Steel	Weight: 208 g
	Author: Jordi Marsà	26/04/2018	Scale: 1:2
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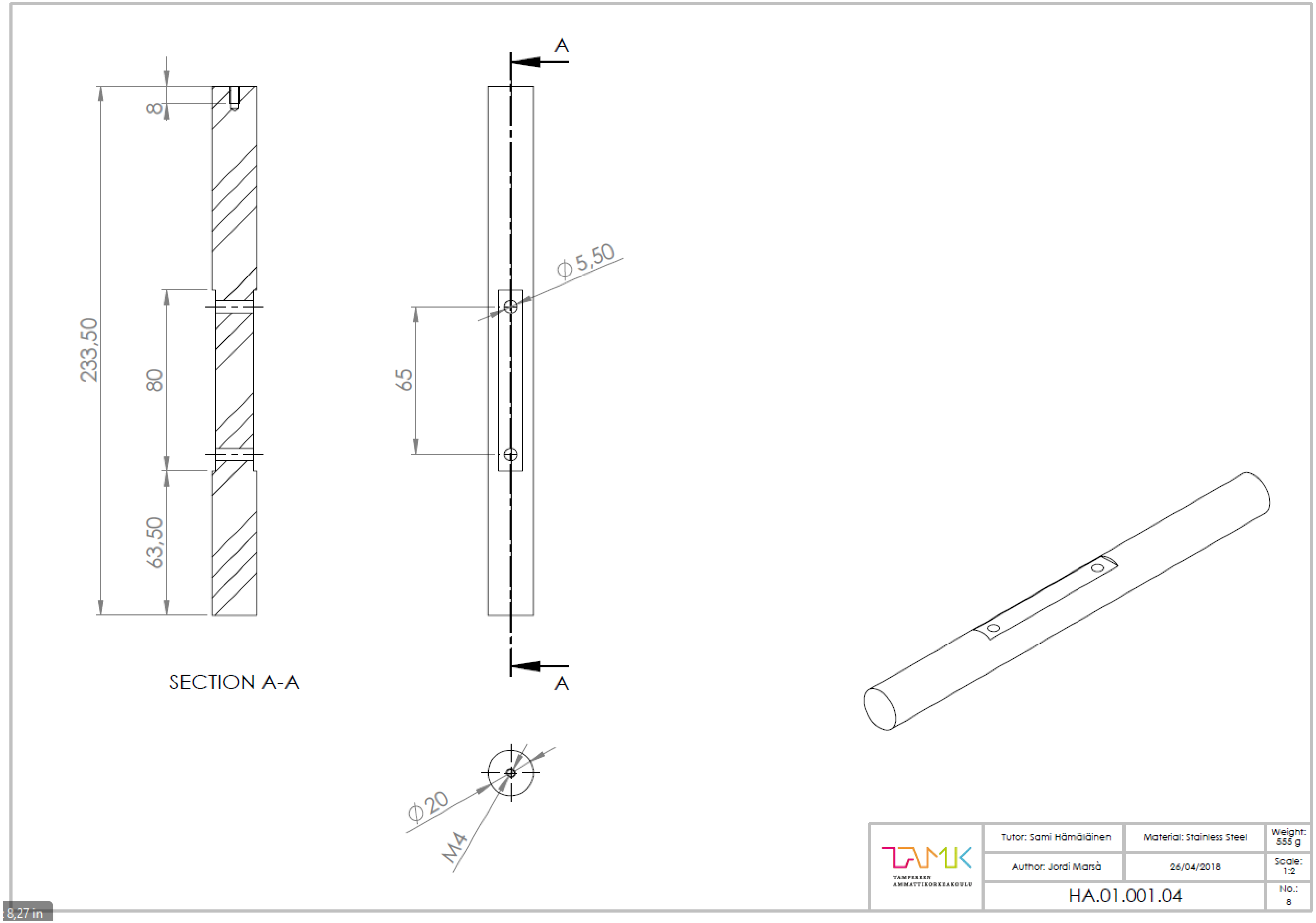
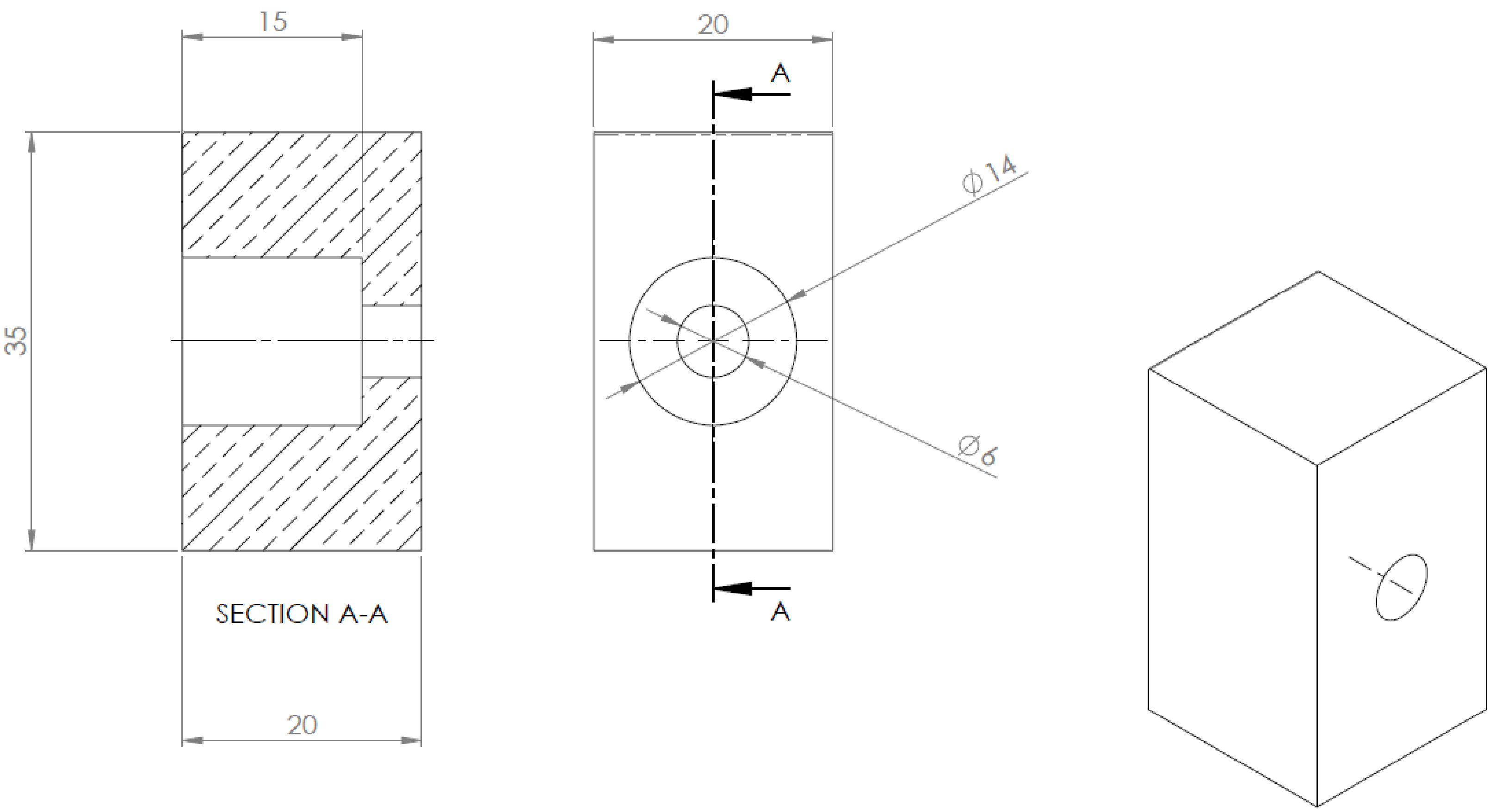
8,27 in


A
A
8
233,50
80
63,50
SECTION A-A
65
ϕ 5,50
ϕ 20
M4
Tutor: Sami Hämäläinen
Material: Stainless Steel
Weight: 555 g
Author: Jordi Marsà
26/04/2018
Scale: 1:2
HA.01.001.04
No.: 8
TAMPEREEN AMMATTIKORKEAKOULU
8,27 in



TAMK TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: Aluminium	Weight: 31 g
	Author: Jordi Marsà	26/04/2018	Scale: 2:1
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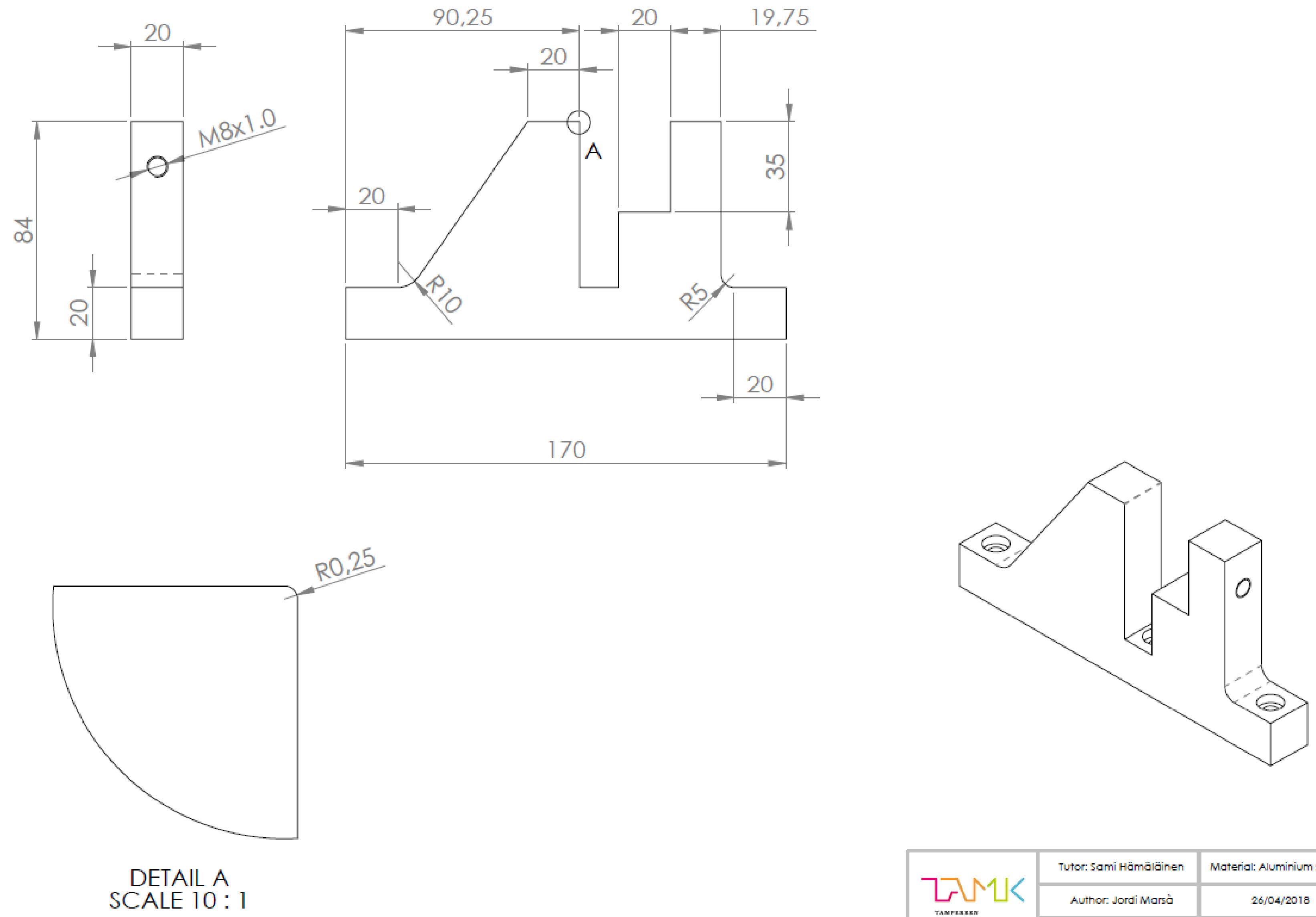
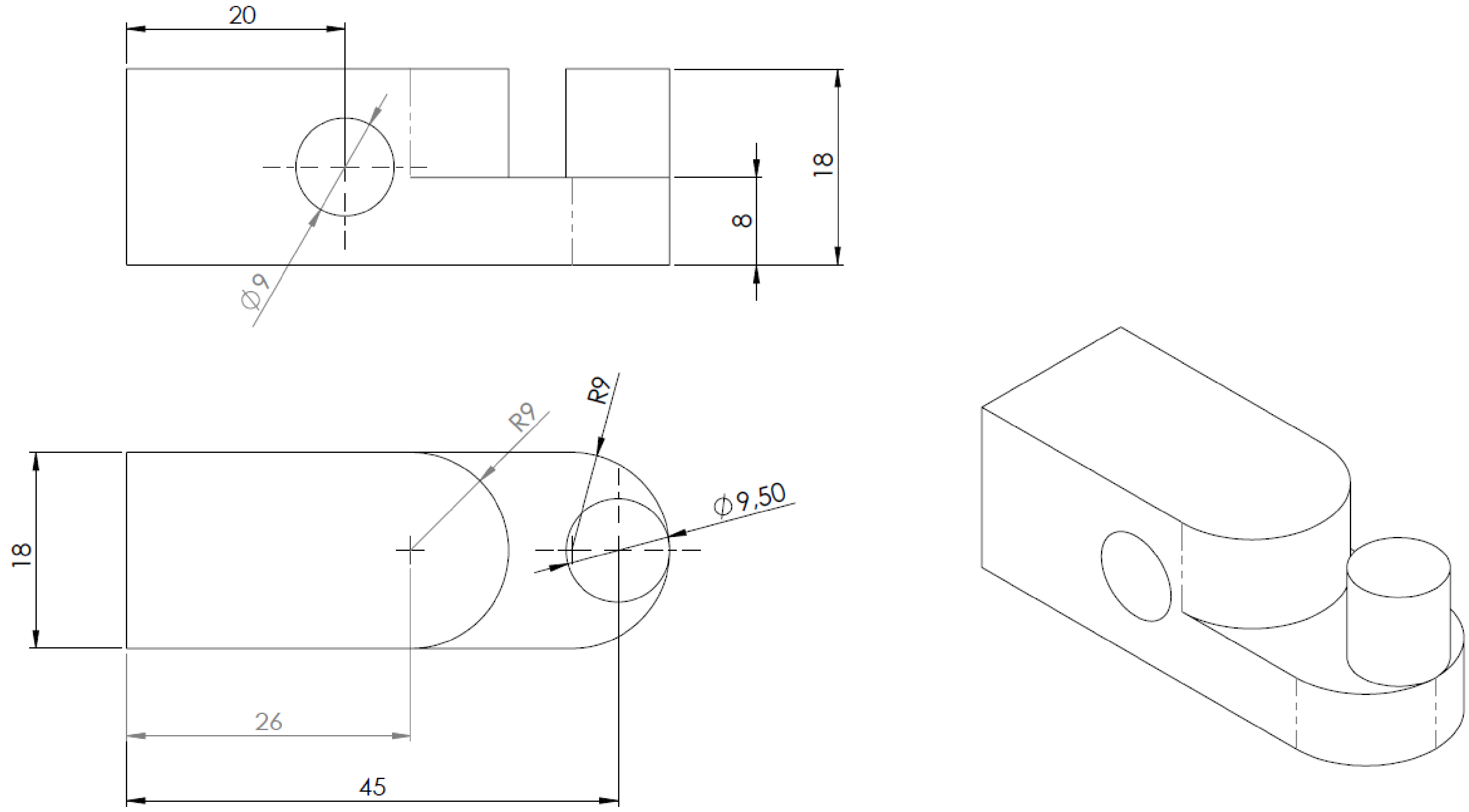
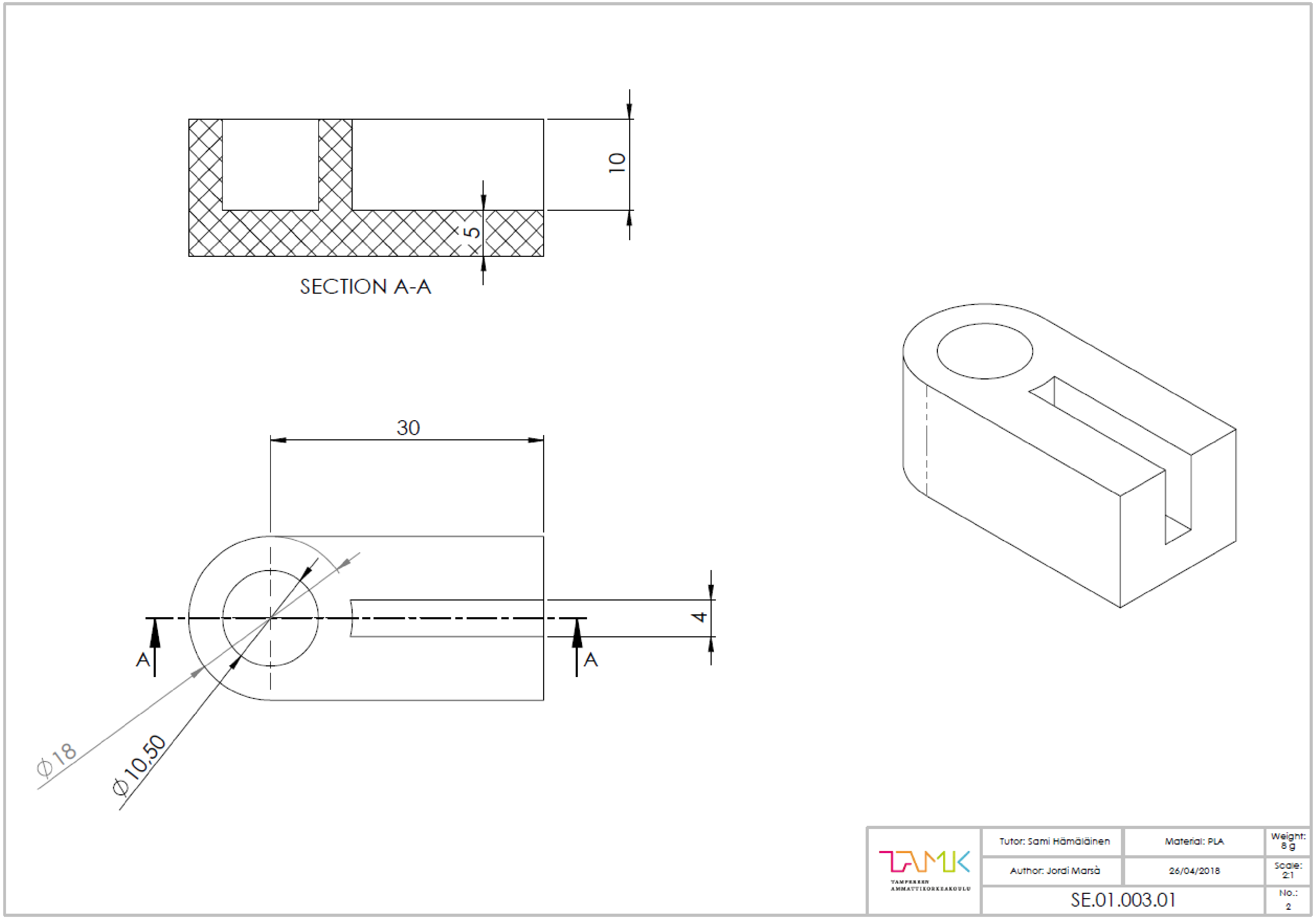
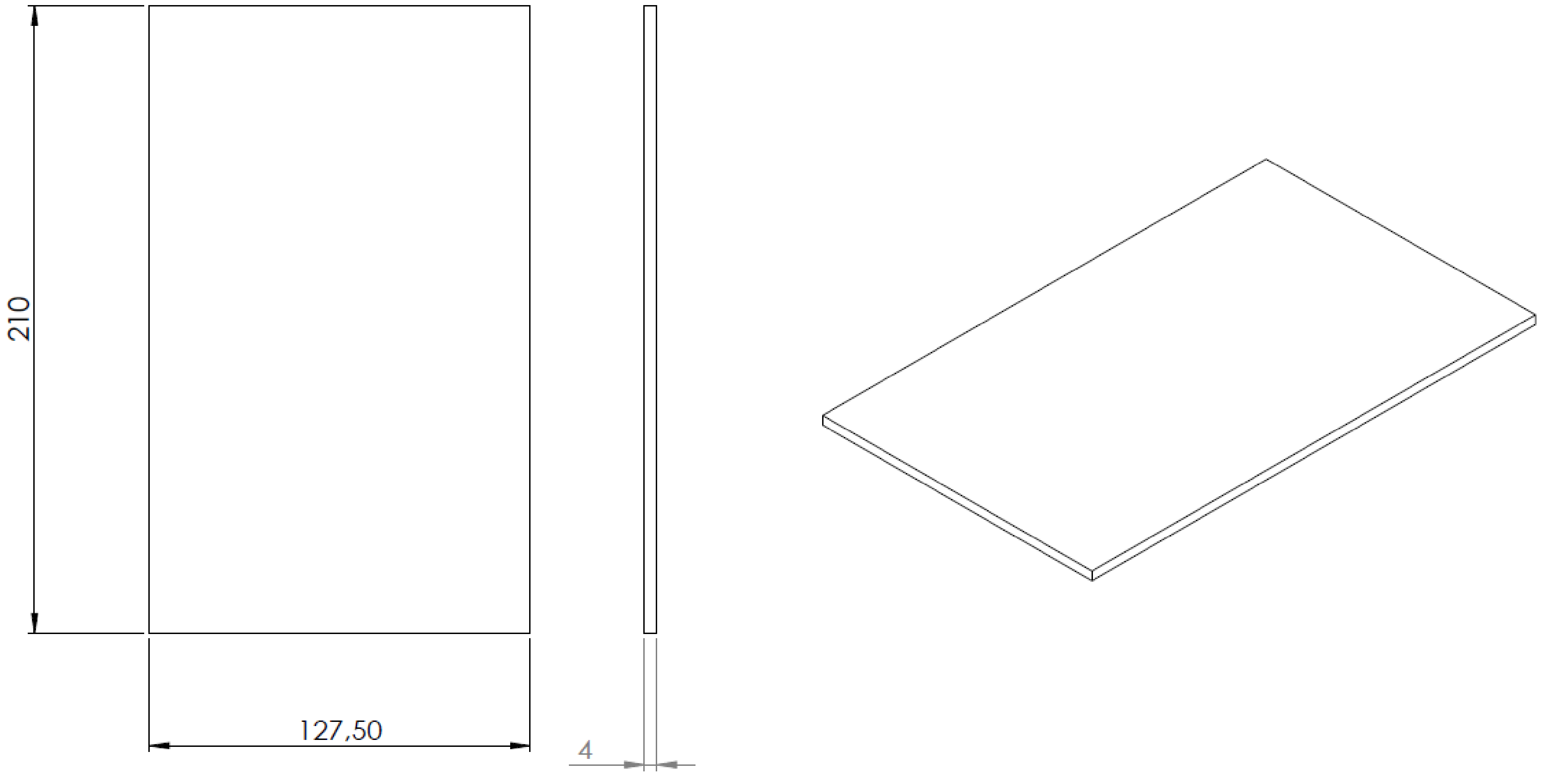


TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: Aluminium 20 mm	Weight: 421 g
	Author: Jordi Marsà	26/04/2018	Scale: 1:2
	SU.01.001.02		No.: 4

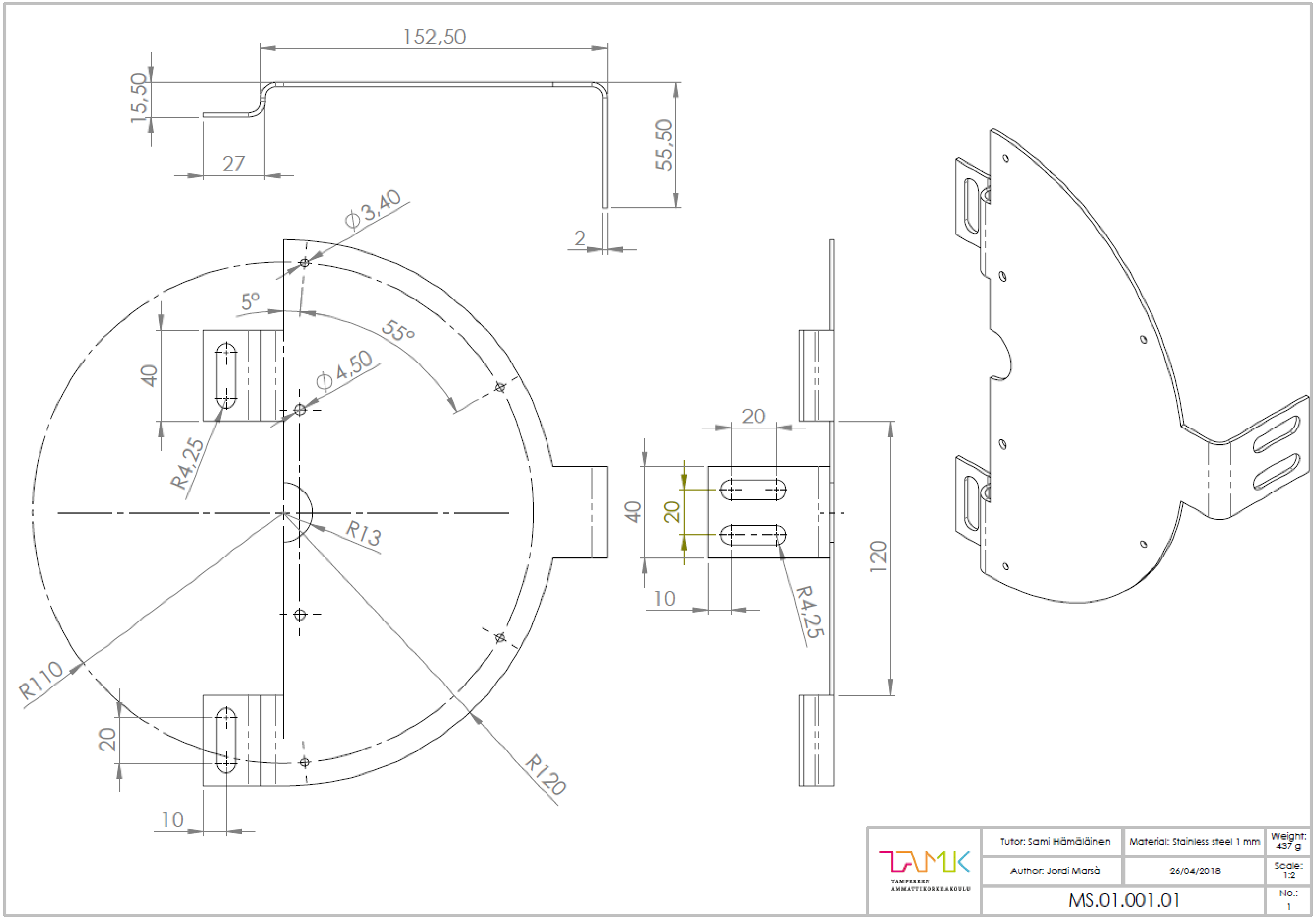


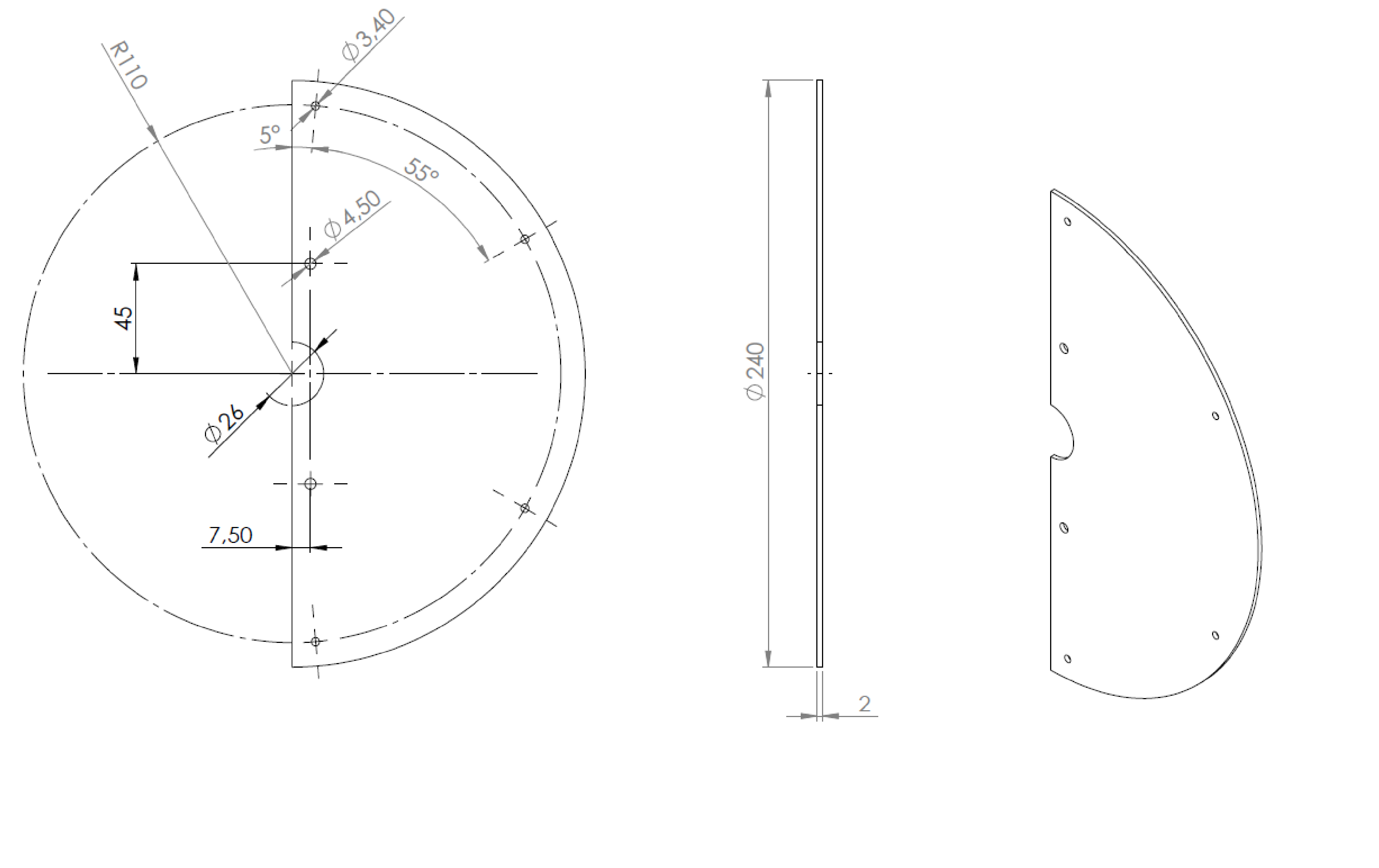
TAMK TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: PLA	Weight: 13g
	Author: Jordi Marsà	26/04/2018	Scale: 2:1
	SE.01.002.01		No.: 1


10
5
SECTION A-A
30
4
A
A
⌀18
⌀10,50
Tutor: Sami Hämäläinen
Material: PLA
Weight: 8 g
Author: Jordi Marsà
26/04/2018
Scale: 2:1
SE.01.003.01
No.: 2
TAMPEREEN AMMATTIKORKEAKOULU



TAMK TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: Methacrylate 4 mm	Weight: 114 g
	Author: Jordi Marsà	26/04/2018	Scale: 1:2
	SE.01.004.01		No.: 3


152,50
15,50
27
55,50
2
ϕ3,40
5°
55°
40
ϕ4,50
R4,25
R13
R110
R120
20
10
20
40
20
10
R4,25
120
TAMK
TAMPEREEN AMMATTIKORKEAKOULU
Tutor: Sami Hämäläinen
Material: Stainless steel 1 mm
Weight: 437 g
Author: Jordi Marsà
26/04/2018
Scale: 1:2
MS.01.001.01
No.: 1



TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: Methacrylate 2mm	Weight: 48 g
	Author: Jordi Marsà	26/04/2018	Scale: 1:2
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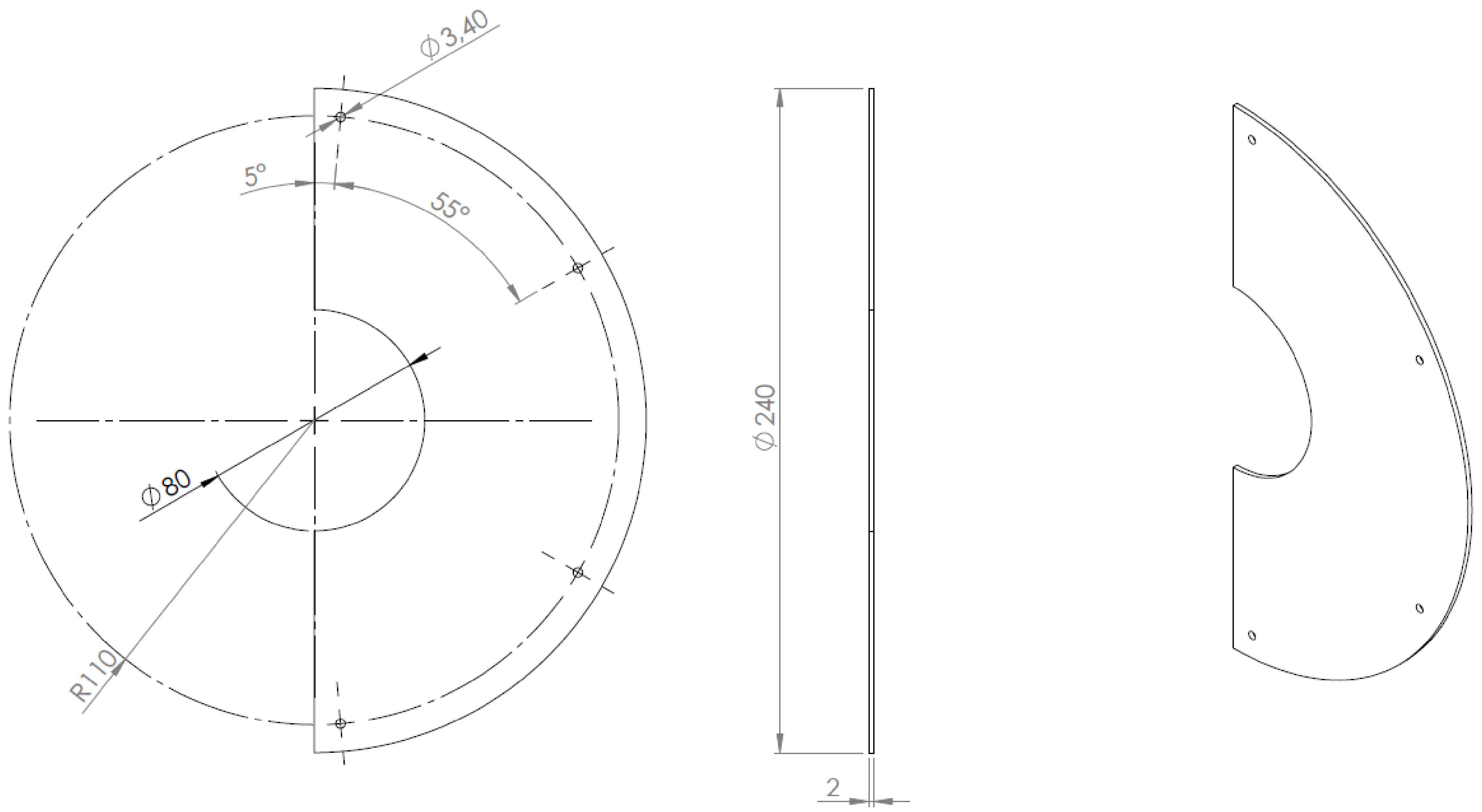

TAMK TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: Methacrylate 2 mm	Weight: 43 g
	Author: Jordi Marsà	26/04/2018	Scale: 1:2
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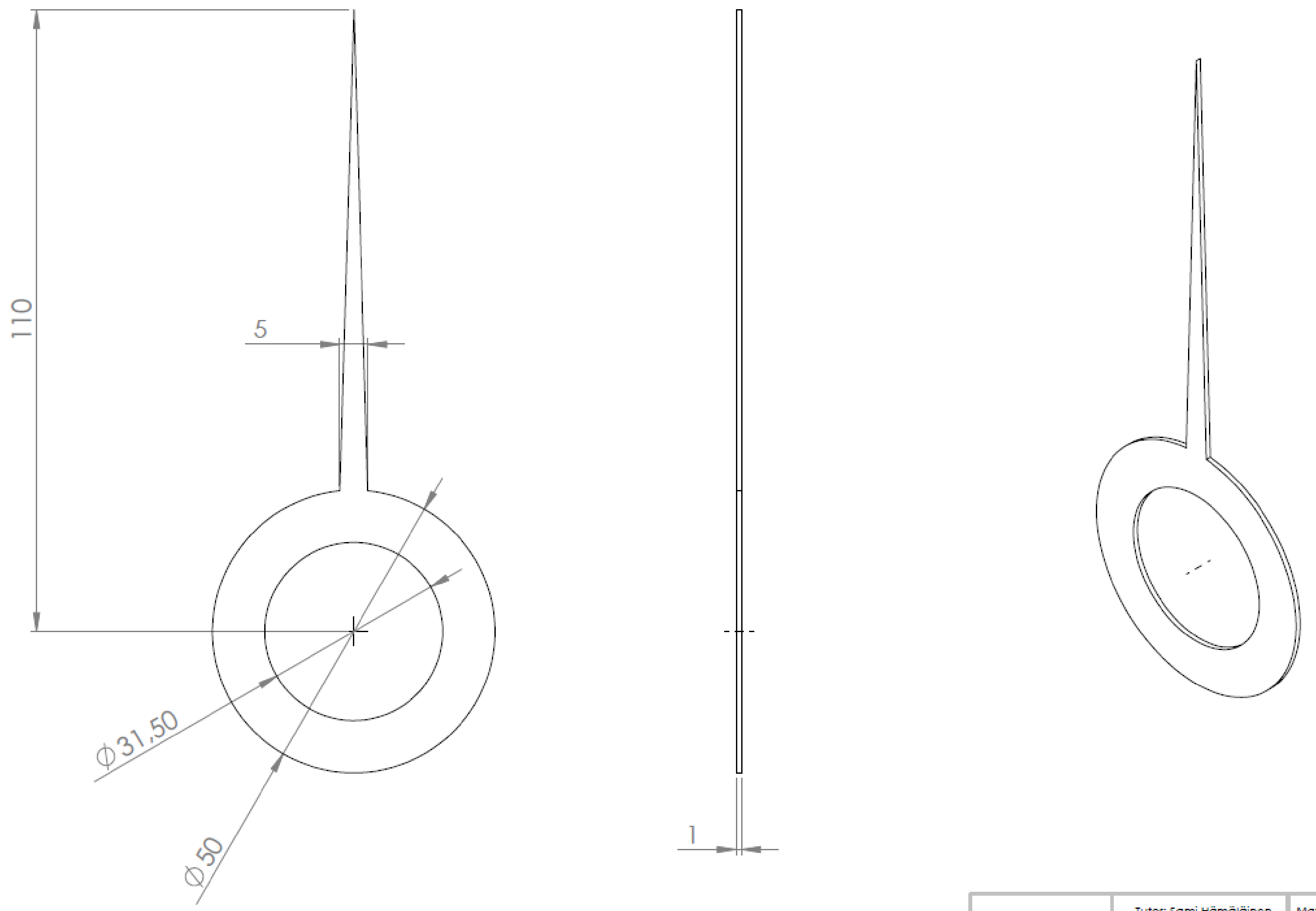
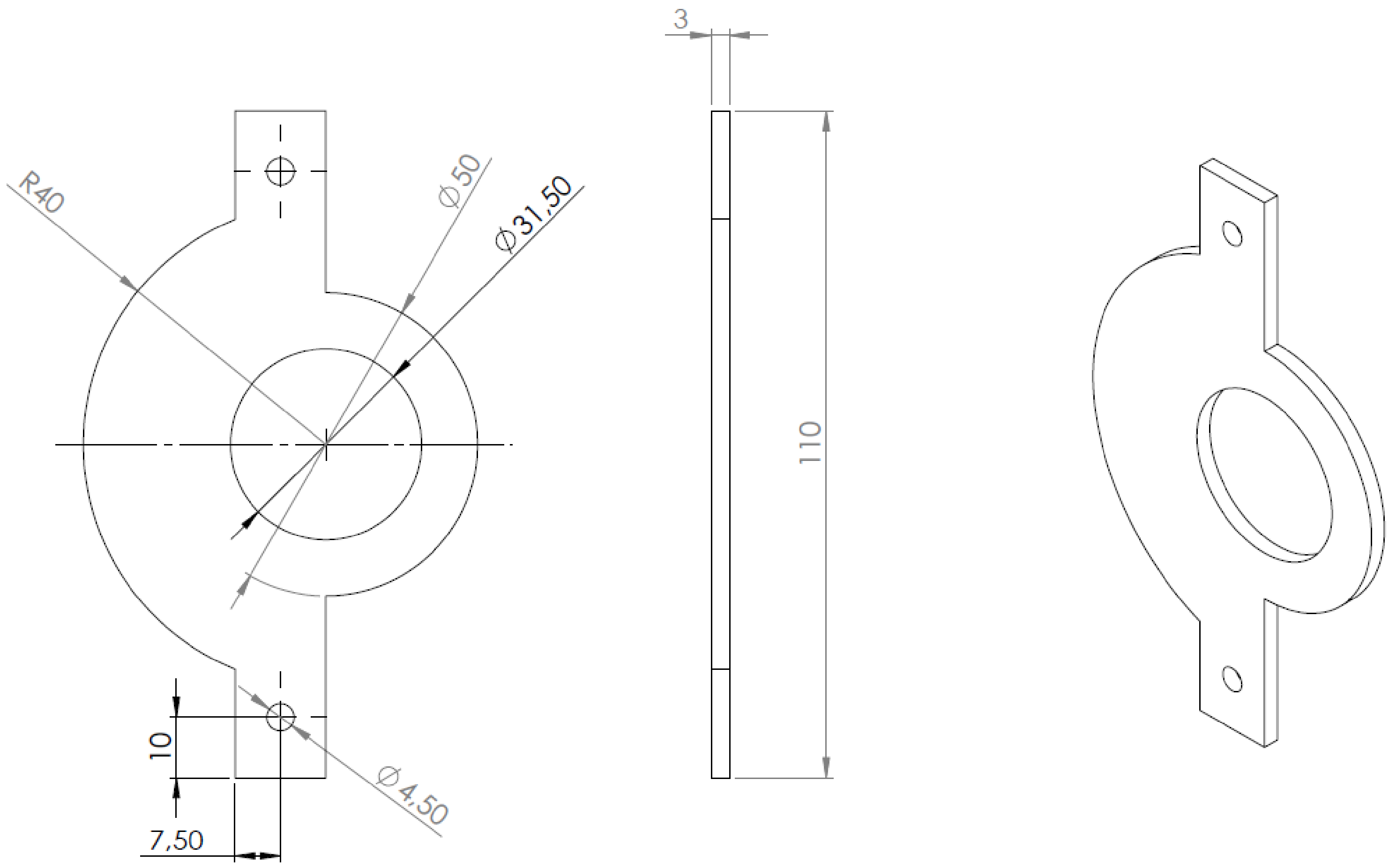
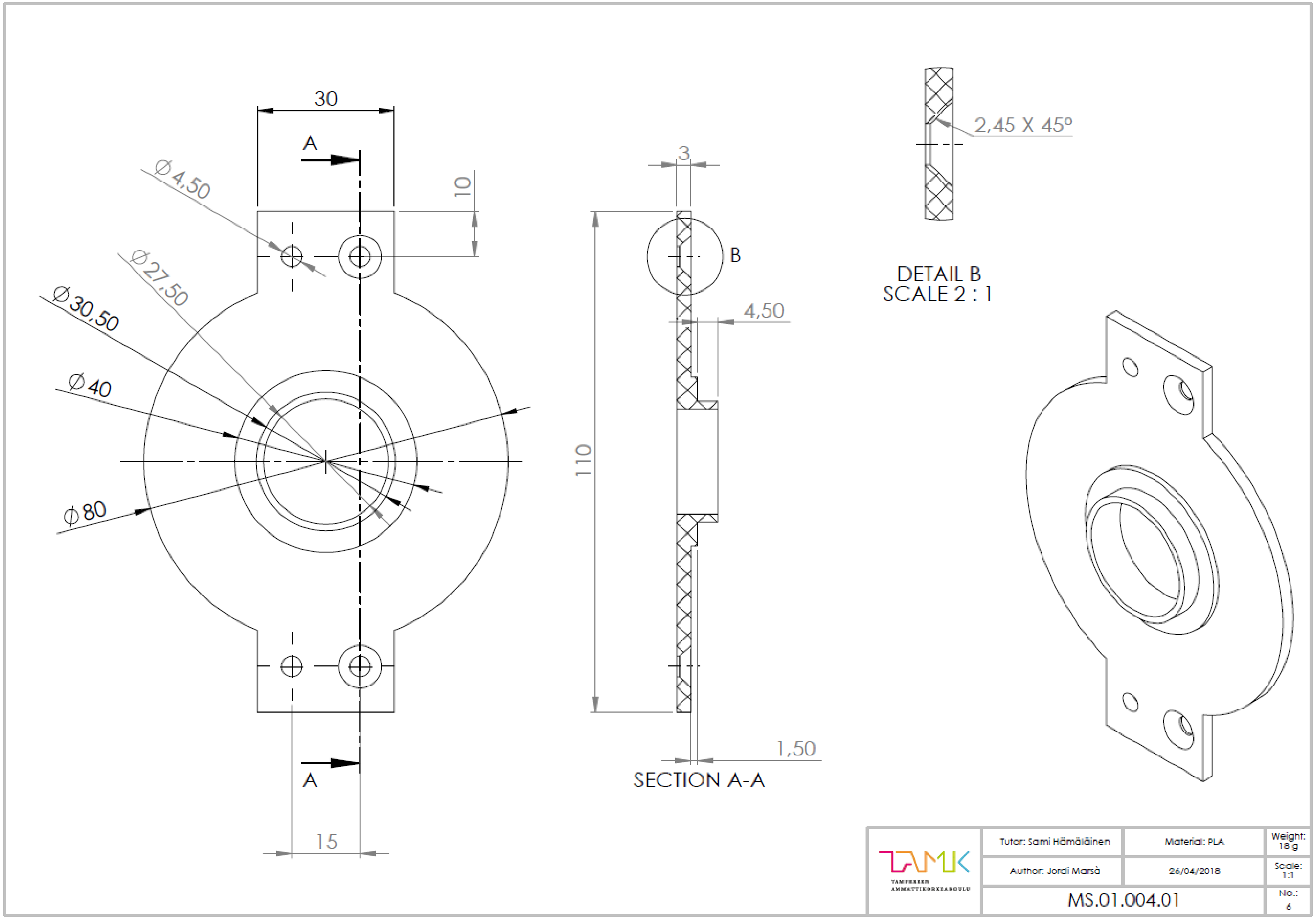
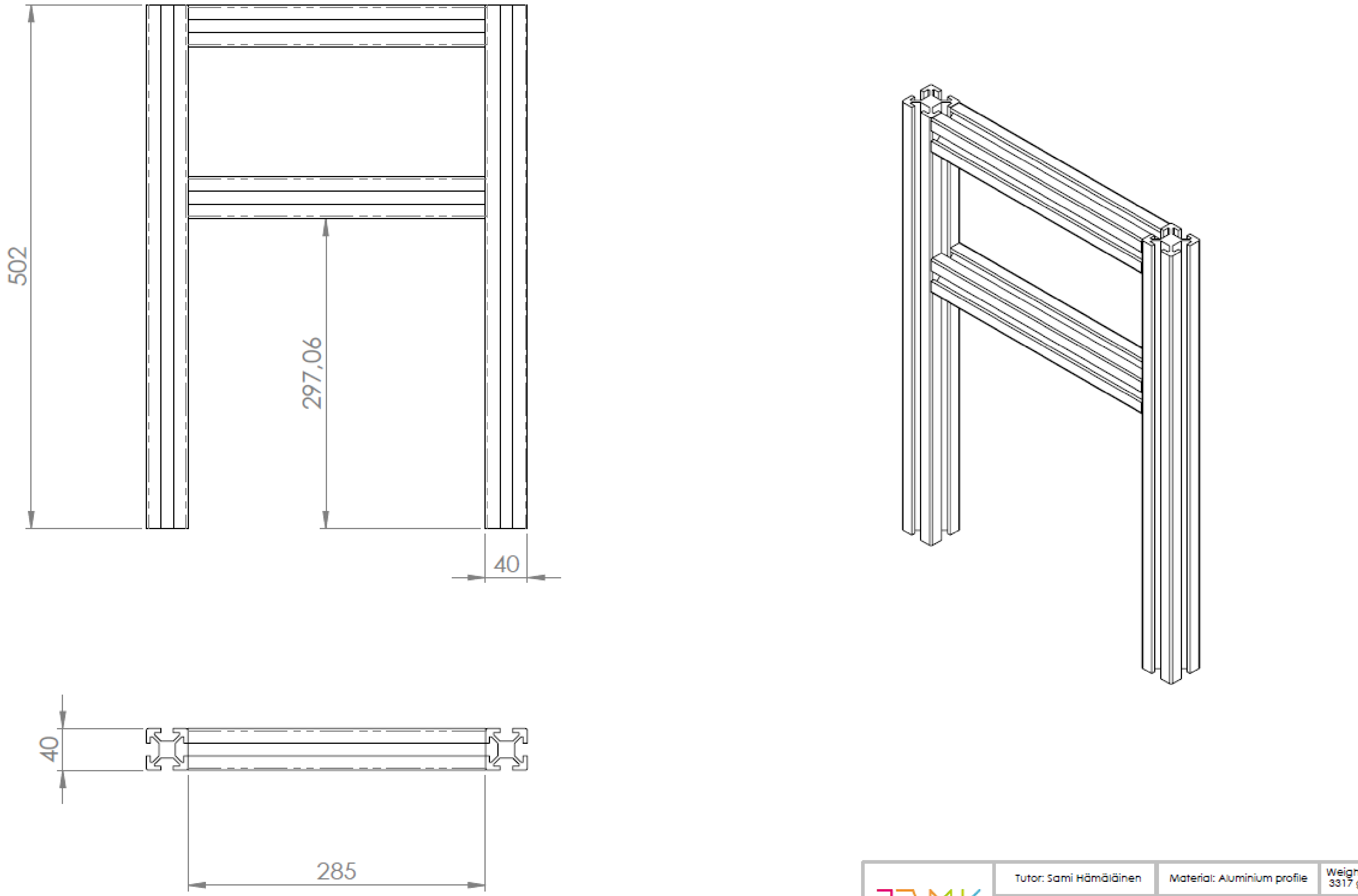


TAMK TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: Stainless Steel 1mm	Weight: 11 g
	Author: Jordi Marsà	26/04/2018	Scale: 1:1
	MS.01.002.01		No.: 4

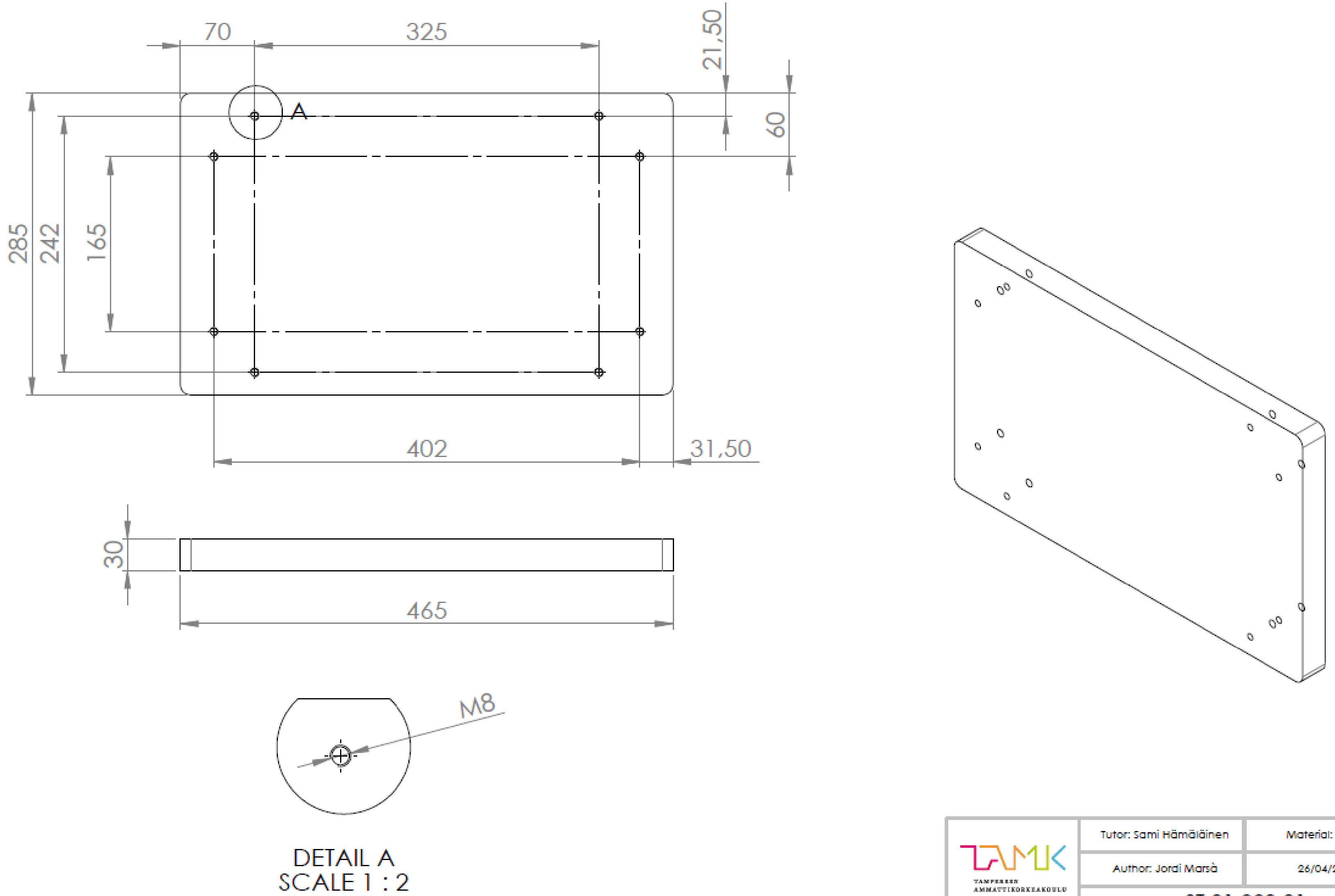


TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: PLA	Weight: 10 g
	Author: Jordi Marsà	26/04/2018	Scale: 1:1
	MS.01.003.01		No.: 5


30
A
10
Ø 4,50
Ø 27,50
Ø 30,50
Ø 40
Ø 80
A
15
3
B
4,50
110
1,50
SECTION A-A
2,45 X 45º
DETAIL B
SCALE 2 : 1
TAMK
TAMPEREEN AMMATTIKORKEAKOULU
Tutor: Sami Hämäläinen
Material: PLA
Weight: 18 g
Author: Jordi Marsà
26/04/2018
Scale: 1:1
MS.01.004.01
No.: 6



TAMK TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: Aluminium profile	Weight: 3317 g
	Author: Jordi Marsà	26/04/2018	Scale: 1:5
	ST.01.001.02		No.: 1



TAMK TAMPEREEN AMMATTIKORKEAKOULU	Tutor: Sami Hämäläinen	Material: Wood	Weight: -
	Author: Jordi Marsà	26/04/2018	Scale: 1:5
	ST.01.003.01		No.: 3

Appendix 2. User Manual

Contents

1. Calibration

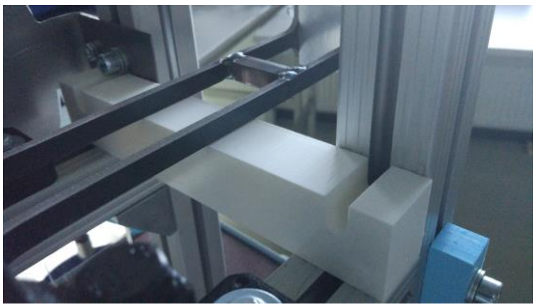
There are some parts that need to be calibrated like the pointer, the hammer and the angle of rising.

There are two things to calibrate in the pointer. The first is the friction of the pointer and the second one is the position of the pointer relatively to the hammer.

To calibrate the friction there are two screws which can be loosened and they are shown in the picture below. It is important that the pointer does not have a lot of friction but it has to be tight enough in order not to go back after a measurement.

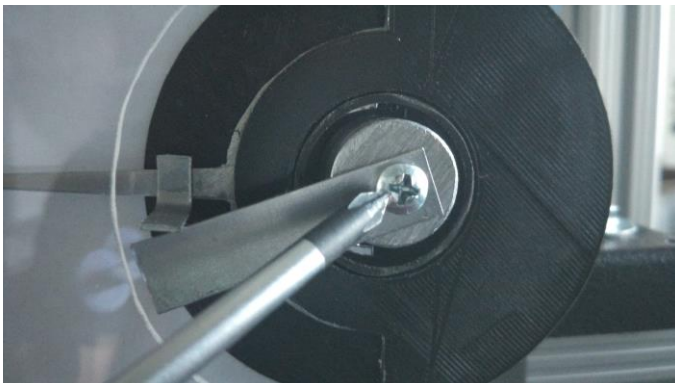
Picture 51 Screws for friction of the pointer

To calibrate the position of the pointer, the hammer has to be placed in 90 degrees (the pointer should be pointing there. To be sure that the hammer is in 90 degrees the security system has to be placed in this way.



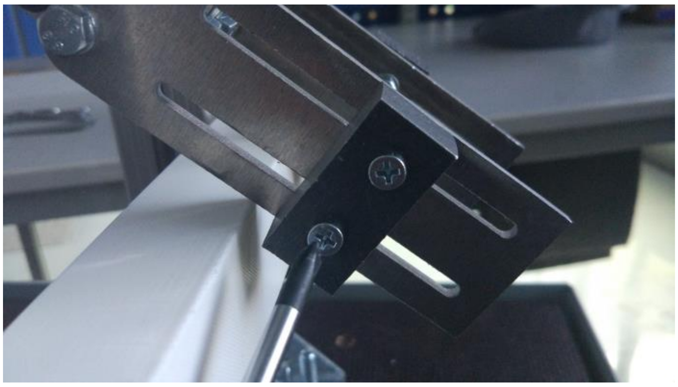
Picture 52 Position for calibration of the pointer

If the pointer it is not in the right position, the screw shown below should be loosened and screwed again in the right position.



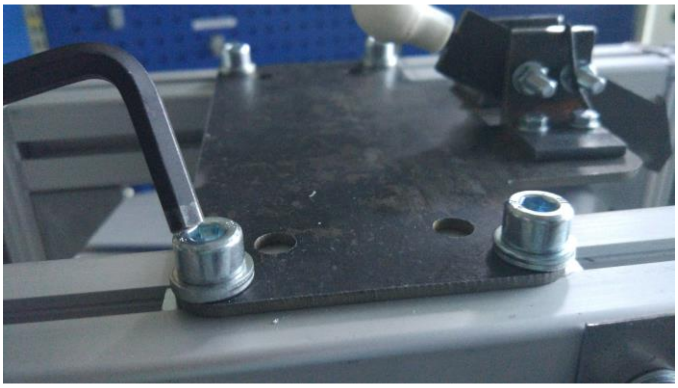
Picture 53 Screw to calibrate the pointer

In the hammer it is possible to calibrate the position of the centre of percussion. This should be done if there are too much vibration in the frame or there are too much losses without a clear explanation. The procedure to calculate the centre of percussion is given in the test chapter. The centre of percussion shall be in the same place as the striking edge. That means exactly 271 mm from the axis of rotation. To change the position of the centre of percussion the two counterweights, shown in the picture below, shall be moved up or down. If they are moved up the centre of percussion it is going to be closer to the axis of rotation. Otherwise, if it is moved down the centre of percussion will be further to the axis. When calibrating this part it is important to place both counterweight in the same height with an error of ±1mm.



Picture 54 Screws to move the counterweight

Finally to calibrate the releasing angle, it should be moved the whole releasing system. It is likely that this does not need a calibration. In case it needed, the four bolts should be unscrewed and moved until the desired place.



Picture 55 Screws to calibrate the releasing angle

In case that the releasing system had problems to hold the hammer the upper part of the frame should be moved, but never the lower.

2. Test specimens

The test specimens shall be as determined in the standards. The length shall be 80±2mm. The width shall be 10±0.2 mm and the thickness shall be 4±0.2 mm. However, it can be made longer or shorter depending on the resistance of the material in order to have a more accurate measurement. Furthermore, all the specimens shall have a notch, just in the middle of the length, with the specifications in the figure below. There are two kinds of notch.

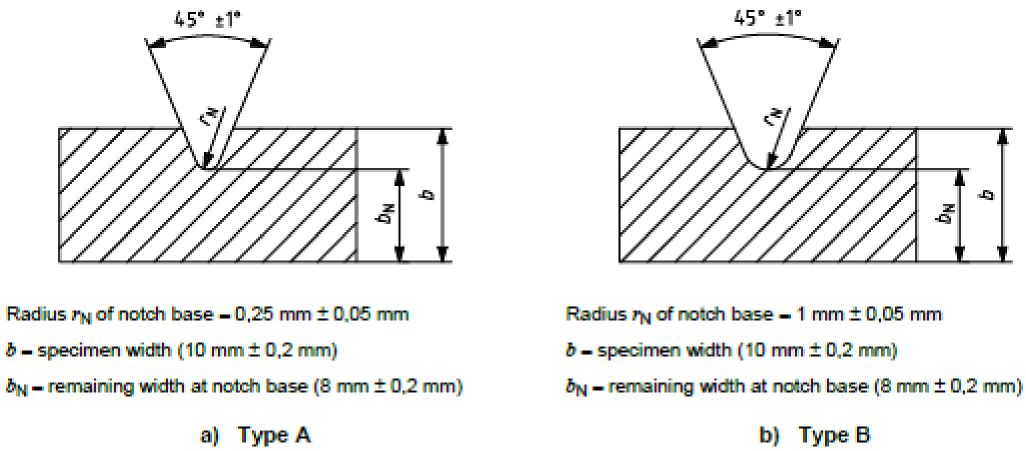


Figure 12 Specimen notch shape and size

Those are the standard specimens, but it can also be done without the notch. However, the test with different specimens cannot be compared.

When testing a material, a set of 10 specimens shall be tested to get a more accurate result.

3. Procedure for testing

First of all, measure the thickness h and width b of each specimen, in the centre, to the nearest 0.02 mm. In the case of notched specimens, carefully measure the remaining width b_N to the nearest 0.02 mm.

Now it is needed to calculate the potential energy of the pendulum. To do that the hammer shall be taken, by the same place where the releasing system holds the hammer, with a dynamometer. The distance from the axis of rotation to that point is 168.5 mm and using the equation below it is possible to know the potential energy of the hammer.

$$E_P = L \cdot F \cdot (1 + \sin(\theta_R))$$

For this case, it would be just needed to calculate the next

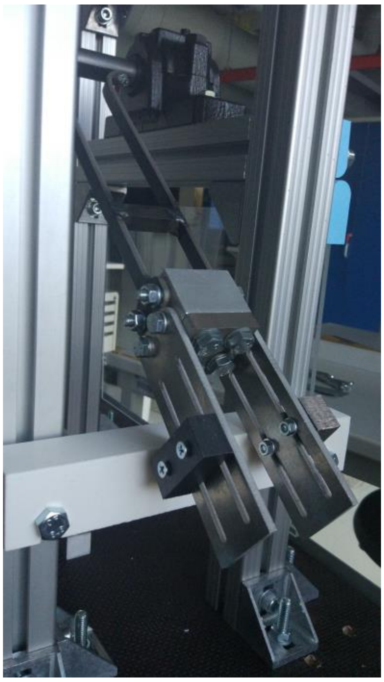
$$E_P = 314.43 \cdot F$$

Where F is the force measured in Newton.
This has to be done if there has been a calibration of the centre of percussion of the hammer or the releasing angle changes.

Now, it is important to check that the theoretical energy absorbed for the specimen is between 10 and 80% of the energy potential of the hammer. If it is not, it is allowed to change the specimen width making it larger or shorter. It is always preferable not to be so close to the 10 and 80%.

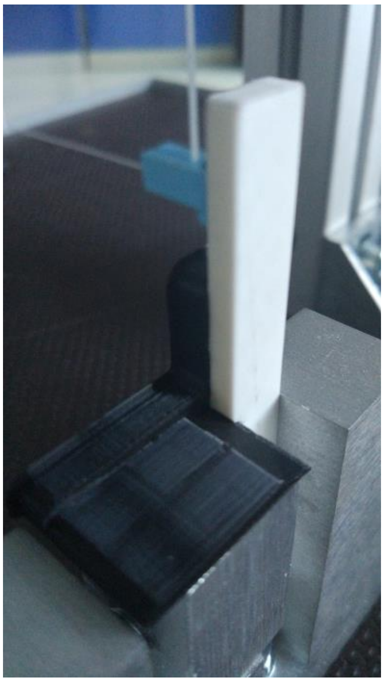
Determine the losses using the procedure mentioned in testing chapters above. Using this it is possible to know the losses due to the friction.

Next, put the hammer in the security system as shown in the picture below.



Picture 56 Hammer in the security position

Afterwards, use the piece, shown in the picture below, as a template to place the specimen in the clamping block in the right position.



Picture 57 Guide to place the specimen correctly

When this is done, place the hammer in the releasing system, close the doors of the security system and remove the security which was holding the pendulum while changing the specimen.

And now, set the pointer to 0 and release the hammer. If the user does not want to wait until the pendulum stops swinging, it is possible to stop the hammer securely. After one or more swinging it is possible to take the hammer in the higher place, never when it is going up, just after having reached the highest point. It is also forbidden to stop it opening the security doors. They can only be opened when the hammer is stopped.

After that, note down the measurement of the pointer and the type of break that it had. There are four kinds of breaking:

- C: Complete break: a break in which the specimen separates into two or more pieces.
- H: Hinge break: an incomplete break such that both parts of the specimen are held together only by a thin peripheral layer in the form of a hinge having low residual stiffness.
- P: Partial break: an incomplete break that does not meet the definition for hinge break.
- N: Non-break: there is no break, and the specimen is only bent and pushed through the support blocks, possibly combined with stress whitening.

4. Calculation and expression results

For the calculus, the first is taking the angle measures. After that, it has to be calculated the energy for each angle and make the average. Although it could be made the angles average, this is not correct because the result is not the same. Using this equation

$$W = L \cdot F \cdot (1 + \cos(180 - \theta_R))$$

It is possible to calculate the energy spent for the failure of each specimen. Afterwards, it has to be made the average of the 10 specimens broken. The formula for this is simple

$$\overline{W} = \frac{\sum_{i=0}^{9} W_i}{10}$$

Once done this, there is just left to calculate the impact resistance this value has to be given divided by the section. The section in the notch which is smaller than in other parts. The width in the notched part is b_N and the thickness is h.

$$W_{r,material} = \frac{\overline{W}}{h \cdot b_N}$$

This value is always given in J/m^2.

5. Maintenance and troubleshooting

For the maintenance the most important is to lubricate the bearings and the seals. In order not to lose energy it is essential to have a lubricating system.

The most common trouble that can be found is when removing the specimen from the clamping block. When the clamping block is pulled back, it can occur that the black piece, in the picture below, detach itself from the axis.

Picture 58 Circlip used to pull back the clamping block

If this happen, it can be used the tools in the following picture made of steel sheet in order to assembly it again. It can be quite complicated in first instance. However, after some attempts it is possible to do it quite easy.

Picture 59 Tools to attach the circlip

6. Safety

The safety is always the most important. For that reason, here there are some instructions of usage and forbidden ways to use this machine.

- When changing the specimen, use always the security system, do not trust at all the releasing system to hold the hammer. If it dropped the pendulum by mistake, it would be dangerous.
- When pendulum is moving it is forbidden to open the security doors, so it is not allowed to introduce the hands or any other thing in the impact zone. Understanding this zone as the highest speed zone of the hammer trajectory.
- It is recommended to wait until the hammer stops by itself. In case there is a need to stop it faster, it is forbidden to do it with an object. Shall be done by hand protected with security gloves. And it has to be just after the hammer reaches the highest point of the trajectory when the pendulum is stopped by a moment and the speed is really lower.
- It is forbidden to place the hammer in the releasing system before closing the security doors.
- Before placing the hammer in the releasing system the security support shall be removed, in order not to have the hands in the pendulum trajectory while the hammer is in the releasing system.
- It is forbidden to use the machine when there is somebody in a radius of two meter from the centre of the machine, who is not protected by the security system.
- The machine shall be used with protection glasses.
- In the possible trajectory of the broken specimen should not be any person who could be damaged when testing some samples.
- This machine is for plastics, it is forbidden to use it with metals, fragile materials such glass and others which can be known from the beginning that are more resistant than the machine is able to broke.
- The machine has to be used with standard specimens, it cannot be introduced any part of a machine or any rare shape.
- This machine shall be used standing, it is forbidden to be sitting while testing a specimen.

- If some changes or calibrations are made, every part of the machine shall be checked. It is forbidden to use the machine if any screw is not well attached or if there is any chance to detach of any part while testing.
- It is forbidden to use the machine if there is any knowledge about the malfunctioning of it.
- If it is noticed that something in the machine is not working as it should. It has to be notified to the responsible person of that machine. And it must be attached a warning saying that is not allowed to use the machine until the reparation of it.

Although these are the safety rules, it is in the user's responsibility to be aware of the dangers of this machine if it is used incorrectly. For that reason, any other security measures can be taken by the user if it is considered more secure for them or any other people around. However, at least, these rules have to be followed for the machine use. Otherwise it is not allowed to use it due to the danger it can suppose the inadequate working.

Appendix 3. Excel tables

For this project there were used some tables to make the orders, as well as to make some calculus. Here they are going to be attached.

Table 5 Calculus of the required energy to break a sample

j/m	j/m2	j
65	6397,6378	0,20472441
80	7874,01575	0,2519685
14	1377,95276	0,04409449
16	1574,80315	0,0503937
20	1968,50394	0,06299213
30	2952,75591	0,09448819
40	3937,00787	0,12598425
50	4921,25984	0,15748031
30	2952,75591	0,09448819
35	3444,88189	0,11023622

This table was used to know the resistance of the materials that the university wanted to test with this machine.

In the following table it is possible to see the list of all the parts of the machine.

Table 6 List of materials and parts used for the whole system

Ensemble	Subset	No.	Name	Material	Quantity
Structure	-	ST.01.001.02	Frame	Aluminium profile	2
Structure	-	ST.01.003.01	Foundation	DIN 1.0501 Steel (C35)	1
Structure	-	-	Angle (4040)	-	20
Structure	-	-	Cap aluminium profile	-	4
Structure	T-nuts	-	T-nut M8 (4040)	-	44-8
Structure	Bolts	-	M8x(12-19)	-	40
Structure	Bolts	-	M8x(XXX+2)	-	4
Structure	Bolts	-	M6x23	-	2
Support	-	SU.01.001.02	Support block	Aluminium 6061	1
Support	-	SU.01.002.02	Clamping block	Aluminium 6061	1
Support	-	SU.01.003.01	Vice	INOX 304	1
Support	-	SU.01.004.01	Knob	DIN 1.1191 (C45)	1
Hammer	-	HA.01.002.02	Strike surface	3D printed steel	1
Hammer	-	HA.01.003.04	Hammer arm	Aluminium 6061	1
Hammer	-	HA.01.005.04	Merge part	Aluminium 6061	1

Hammer	-	HA.01.001.02	Axis	INOX 304	1
Hammer	-	HA.01.006.01	Leg	DIN 1.0501 Steel (C35)	2
Hammer	-	HA.01.004.04	Weight	Aluminium	2
Hammer	Bearings	-	Precision radial bearing	-	2
Hammer	Bolts	-	M5x25	-	2
Hammer	Bolts	-	M6x25	-	4
Hammer	Bolts	-	M6x20	-	4
Hammer	Bolts	-	M8x28	-	4
Hammer	Bolts	-	M5x12	-	2
Hammer	Nuts	-	M5	-	2
Hammer Keeper	-	HK.01.003.02	Surface	Aluminium	1
Hammer Keeper	-	HK.01.001.02	Lever support	DIN 1.0402 Steel (C15) (2mm)	2
Hammer Keeper	-	HK.01.004.02	Lever axis	DIN 1.0402 Steel (C15) (2mm)	2
Hammer Keeper	-	HK.01.005.01	Lever	Aluminium 6061	1
Hammer Keeper	-	-	Torsion spring	-	1
Hammer Keeper	-	HK.01.002.02	Handle	3D printed ABS/PLA	1
Hammer Keeper	Bolts	-	M5x10	-	4
Security	-	SE.01.001.01	Hammer sup-port	3D printed ABS/PLA	1
General	Bolts	-	M6x36	-	2
General	T-nuts	-	T-nut M8 (4040)	-	6
General	Nuts	-	M8	-	2

This was the table which provided the parts needed for this machine and was useful for ordering what was needed. However, after some parts were changed and this was not actualised anymore because all the parts were already ordered and it was not necessary.

Here there are three tables that were used to order the parts in three different companies.

Table 7 Bearings order

Ref. number	Part name	Quantity	Total cost (€)
10300001461	1205 EKTN9 Pallomainen kuulalaakeri	2	41,62
10300008493	SNL 505 Laakerinpesä	2	215,43
10300005600	H 205 Kiristysholkki	2	21,54
10300005169	FRB 5/52 Ohjausrengas	2	6,63
10300008934	TSN 505 A Laakeripesän tiiviste	2	33,19
10300004850	ASNH 505 Laakeripesän Päätykansi	1	4,47

Table 8 Aluminium profile order

Ref. number	Part name	Length (mm)	Quantity	Cost/uf (€)	Total cost (€)
1061600	1.11.040040.43LP.60 PROF 40X40 4E LP	915	1	58	58
5038430	1.32.EM8 T-URAMUTTERI E M8 SINK. TERÄS	-	50	1,5	75
1060234	1.46.204.4039.1 KULMA 40X39X38	-	20	3,3	66

Table 9 Laser cut order

Part name	Quantity	Material
HA.01.003.08	1	Steel 4 mm
HA.01.003.08-	1	Steel 4 mm
HA.01.006.05	2	Aluminium 4 mm
HK.01.001.03	2	Steel 3mm
HK.01.003.02	1	Steel 3 mm
HK.01.005.01	1	Steel 5 mm
SU.01.001.03	1	Aluminium 20 mm

All these tables were sent to the companies to order the parts

The last table were the calculus excel. This was for the calculus of centre of percussion, energy and speed.

Table 10 Calculus for the hammer

Mass(g)	Izz(g*mm^2)	Lg (mm)	Lenght	Energy (11 J)	Lf (mm)	Speed
1186,17	136944189,5	297,61	390	6,462209226	387,926237	3,788770571
1186,17	137334866,8	298,02	390	6,471111836	388,497711	3,785982937
1186,17	137730387,7	298,43	390	6,480014446	389,081297	3,783142559
1186,17	138130752	298,84	390	6,488917056	389,676946	3,780250053
1186,17	138535959,9	299,25	390	6,497819666	390,284607	3,777306038

1186,17	138946011,3	299,65	390	6,506505139	390,917278	3,774248156
1186,17	139360906,1	300,06	390	6,515407749	391,548821	3,771203117
1186,17	139780644,5	300,47	390	6,52431036	392,19223	3,768108431
1186,17	140205226,4	300,88	390	6,53321297	392,847458	3,764964721
1186,17	140419333,7	301,08	390	6,537555706	393,186017	3,763343428
1186,17	138315736,1	299,02	390	6,492825519	389,963913	3,778858891
1186,17	138316546,1	299,02	390	6,492825519	389,966196	3,778847826
1186,17	138320596,5	299,03	390	6,493042656	389,964575	3,778855684
1186,17	138324647,3	299,03	390	6,493042656	389,975995	3,778800351
1186,17	138357071,7	299,07	390	6,493911203	390,015238	3,778610238
1186,17	138340855,6	299,05	390	6,49347693	389,995607	3,778705338
1186,17	138373295,5	299,08	390	6,49412834	390,047929	3,778451885
1186,17	138348962,7	299,06	390	6,493694066	390,00542	3,778657799
1186,17	138344908,9	299,05	390	6,49347693	390,007033	3,778649982
1186,17	138342476,9	299,05	390	6,49347693	390,000177	3,778683196
1186,17	138341666,3	299,05	390	6,49347693	389,997892	3,778694267
2469,96	263240112,3	273,15	390	12,35030504	390,176351	3,777830019
1481,3	33366398,07	111,21	225	3,015597835	202,545437	3,02502915
1606,1	43243108,34	124,39	225	3,657165458	216,45063	2,926249609
1511,75	42188113,76	126,38	225	3,497396633	220,816631	2,897176178
1633,07	50013299,96	135,72	225	4,057282156	225,65079	2,86597479
1624,34	49226721,82	134,84	225	4,009426368	224,752863	2,871694122
1565,46	41997658,71	126,11	225	3,613916052	212,73237	2,951712171
1743,98	51683913,93	136,95	225	4,372100093	216,39731	2,926610097
1574,15	48227704,1	133,69	225	3,85240197	229,166721	2,843904577
1427,86	37986681,77	120,54	225	3,150673309	220,706205	2,897900859
1457,11	40133135,3	123,55	225	3,295502517	222,929736	2,883412622
1471,9	41828062,41	125,73	225	3,38769092	226,021903	2,863620959
1470,03	41609847,34	125,45	225	3,375852188	225,631255	2,866098858
1468,15	41392917,67	125,18	225	3,364278467	225,227109	2,868669157
1434,91	48144423,93	111,79	271,022004	2,936392983	300,136198	2,993323409
1434,91	48144423,93	111,79	271,022004	2,936392983	300,136198	2,993323409
1425,81	49713638,98	113,47	271,022004	2,961619565	307,278973	2,958328576
1404,21	45983344,1	108,8	271,022004	2,796710521	300,981356	2,989117813
1392,21	44470240,14	106,69	271,022004	2,719036411	299,392565	2,99703852
1400,85	45985101,28	108,63	271,022004	2,785659135	302,186969	2,983149122
1400,85	45903200,11	108,55	271,022004	2,783607651	301,871075	2,984709581
1396,53	45137796,56	107,58	271,022004	2,750225907	300,440548	2,991806886
1383,33	41115462,76	110,41	271,022004	2,795894403	269,197472	3,160656807
1394,1	42142952,25	111,92	271,022004	2,856197193	270,099218	3,155376352
1394,1	41746318,46	111,48	271,022004	2,844968397	268,613165	3,164092584
1387,82	41094311,16	110,53	271,022004	2,808017895	267,897335	3,168317043
1387,82	41470577,52	110,95	271,022004	2,818688007	269,32684	3,159897626
1381,54	40798262,46	109,97	271,022004	2,781148943	268,536905	3,16454183
1381,54	40870100,66	110,05	271,022004	2,783172149	268,814194	3,162909253
1381,95	41014735,5	110,18	271,022004	2,787286796	269,367265	3,159660505

1505,91	48752801,77	120,38	271,022004	3,318485432	268,934317	3,162202798
1435,03	41026348,94	110,03	271,022004	2,890404685	259,830887	3,217121344
1505,22	48677787,66	120,28	271,022004	3,314209508	268,866957	3,162598889
1517,7	50038887,3	122	271,022004	3,389474134	270,247621	3,15450987
1433,05	48037831,54	124,08	271,022004	3,254990216	270,159514	3,155024215
859,97	47992726,88	206,77	271,022004	3,255047932	269,901065	3,156534434
1300,2	33861738,66	103,42	271,022004	2,461508016	251,822516	3,267875865
1433,05	40000000,56	102	271,022004	2,675765652	273,651909	3,134827075
1433,05	44555137,63	120,1	271,022004	3,15058289	258,876983	3,223043083
1558,75	51763183,19	118,03	271,022004	3,36787088	281,353357	3,091624777
1496,35	43802823,97	108,08	271,022004	2,960500121	270,846724	3,151019109
1456,14	38675561,05	101,21	271,022004	2,697820908	262,427937	3,201163065
1467,63	40140493,31	103,21	271,022004	2,772840687	264,999068	3,185595702
1473,37	40872959,44	104,2	271,022004	2,810386826	266,229724	3,17822441
1488,69	43052886,16	107,01	271,022004	2,916185824	270,254937	3,154467173
1456,14	37860552,85	100,38	271,022004	2,675696698	259,021985	3,222140815
1558,75	48183364,89	114,62	271,022004	3,270569858	269,687151	3,157786055
1574,35	49753953,96	116,63	271,022004	3,361229166	270,966771	3,150321029
1353,43	51853599,93	142,49	271,022004	3,530260428	268,880141	3,162521353
1361,8	52701778,93	143,57	271,022004	3,579015584	269,555529	3,158556921
1389,51	55515526,86	147,06	271,022004	3,740613161	271,68035	3,14618109
1377,53	54299069,16	145,57	271,022004	3,670789722	270,781779	3,15139696
1377,27	54273574,17	145,54	271,022004	3,669340526	270,761533	3,151514777
1384,83	55040178,48	146,48	271,022004	3,713311254	271,334513	3,148185473
1380,15	54564852,91	145,9	271,022004	3,686108724	270,976362	3,150265279

Here there are all the hammer designs made, changing the weight, the position of some parts in order to modify the important properties of the hammer that had an important influence in the project. All these properties were in the requirements of the Izod test.